Searching for Dark Matter in Galactic Substructure

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WH7SW

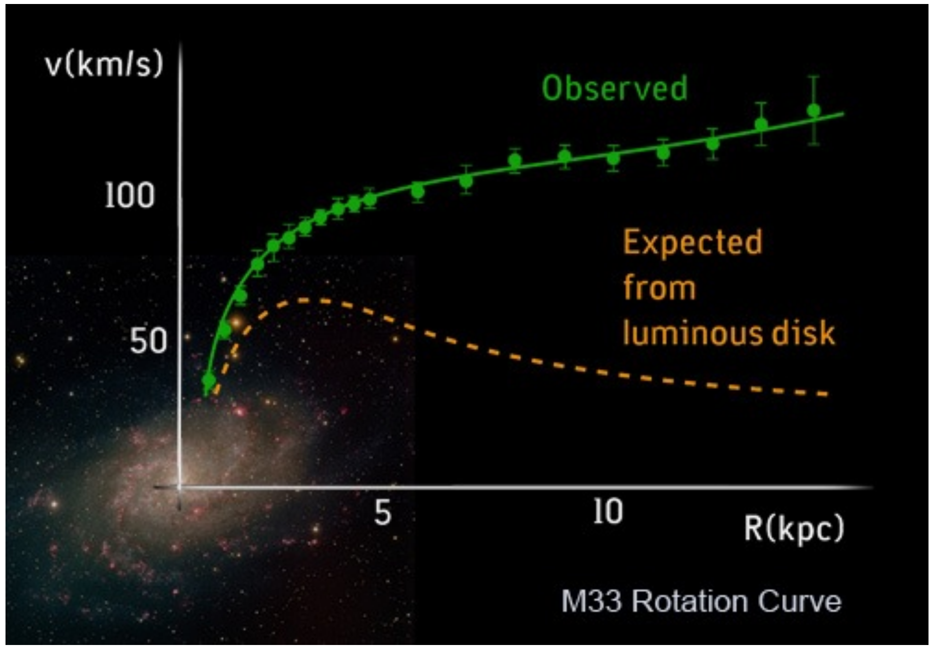
Fermilab Wine & Cheese
February 27th, 2014

Fermilab | Center for Particle Astrophysics

Indirect Detection of Dark Matter

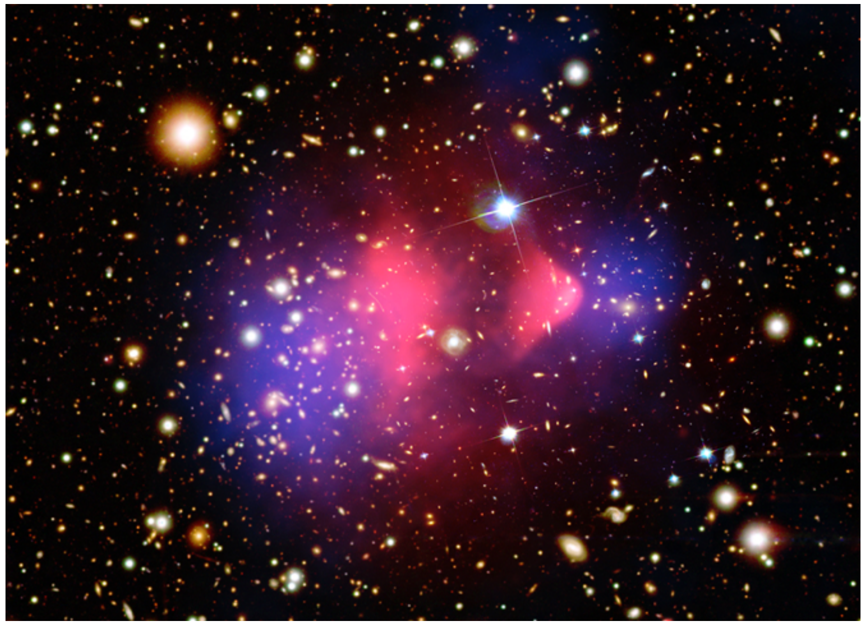
Motivation for Dark Matter

Galaxy Rotation Curves



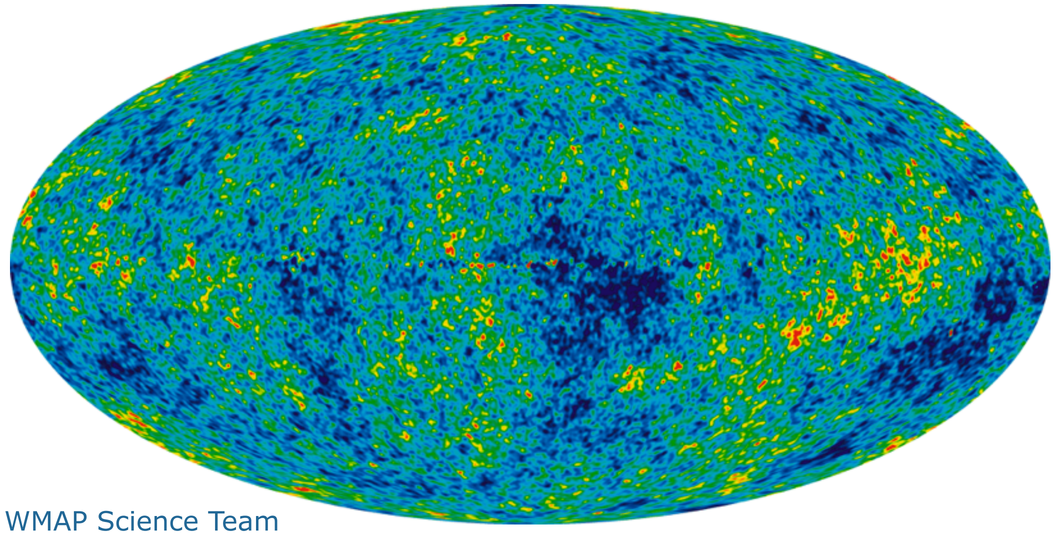
NOAO, AURA, NSF, T.A. Rector

Colliding Clusters

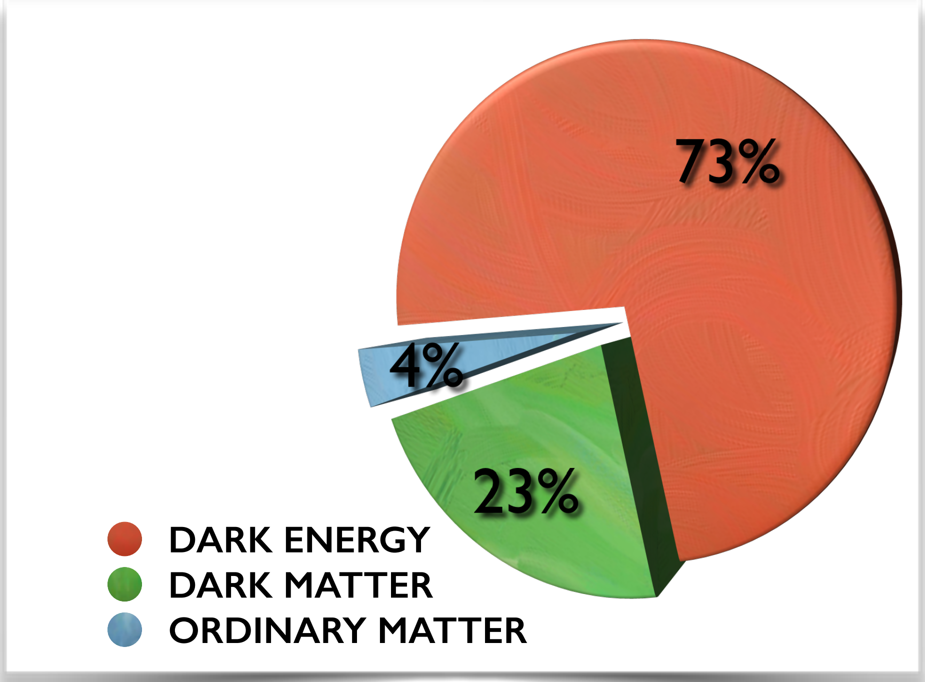


Bullet Cluster (Markevitch & Clowe, 2006)

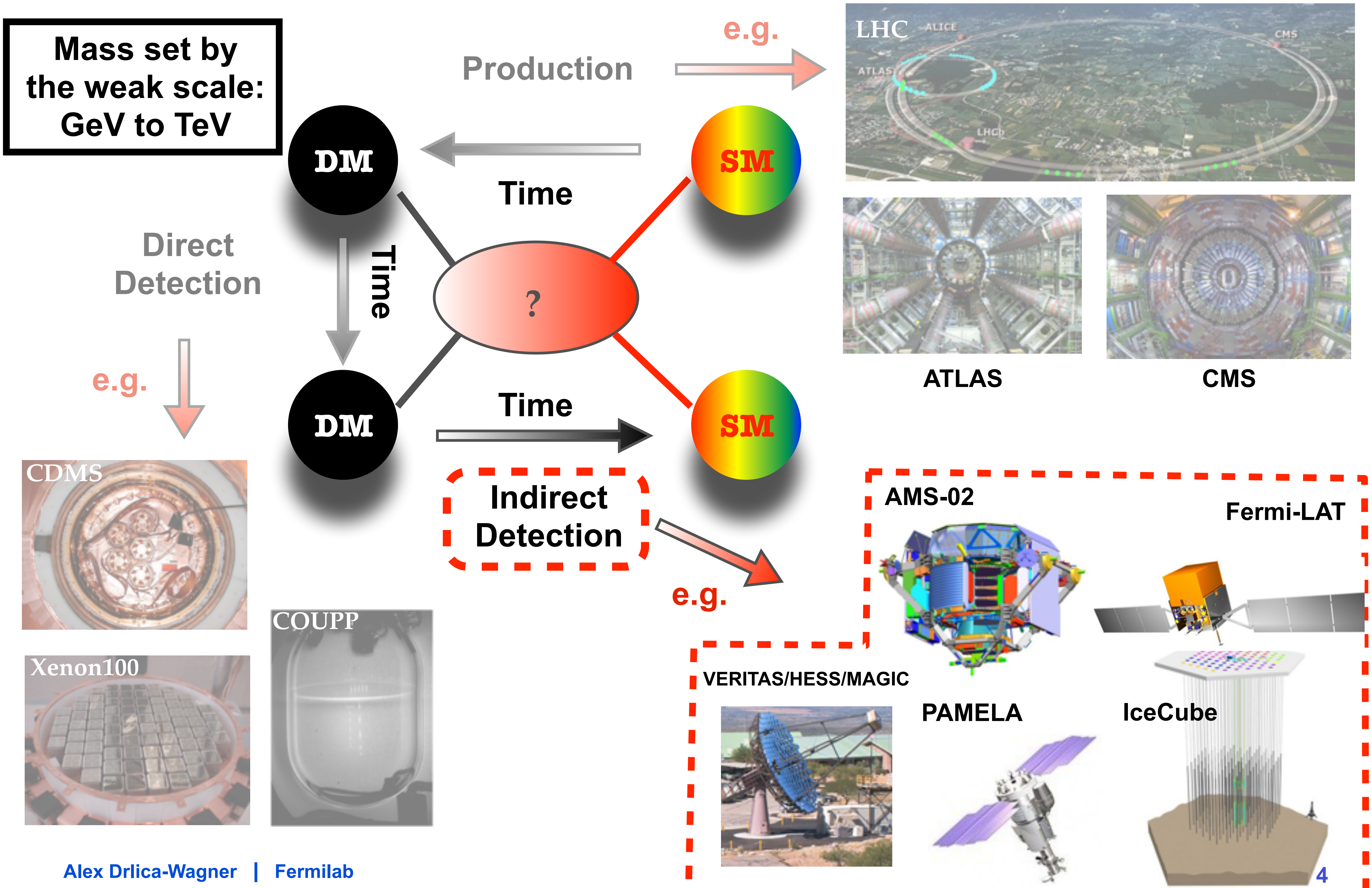
Cosmological Probes



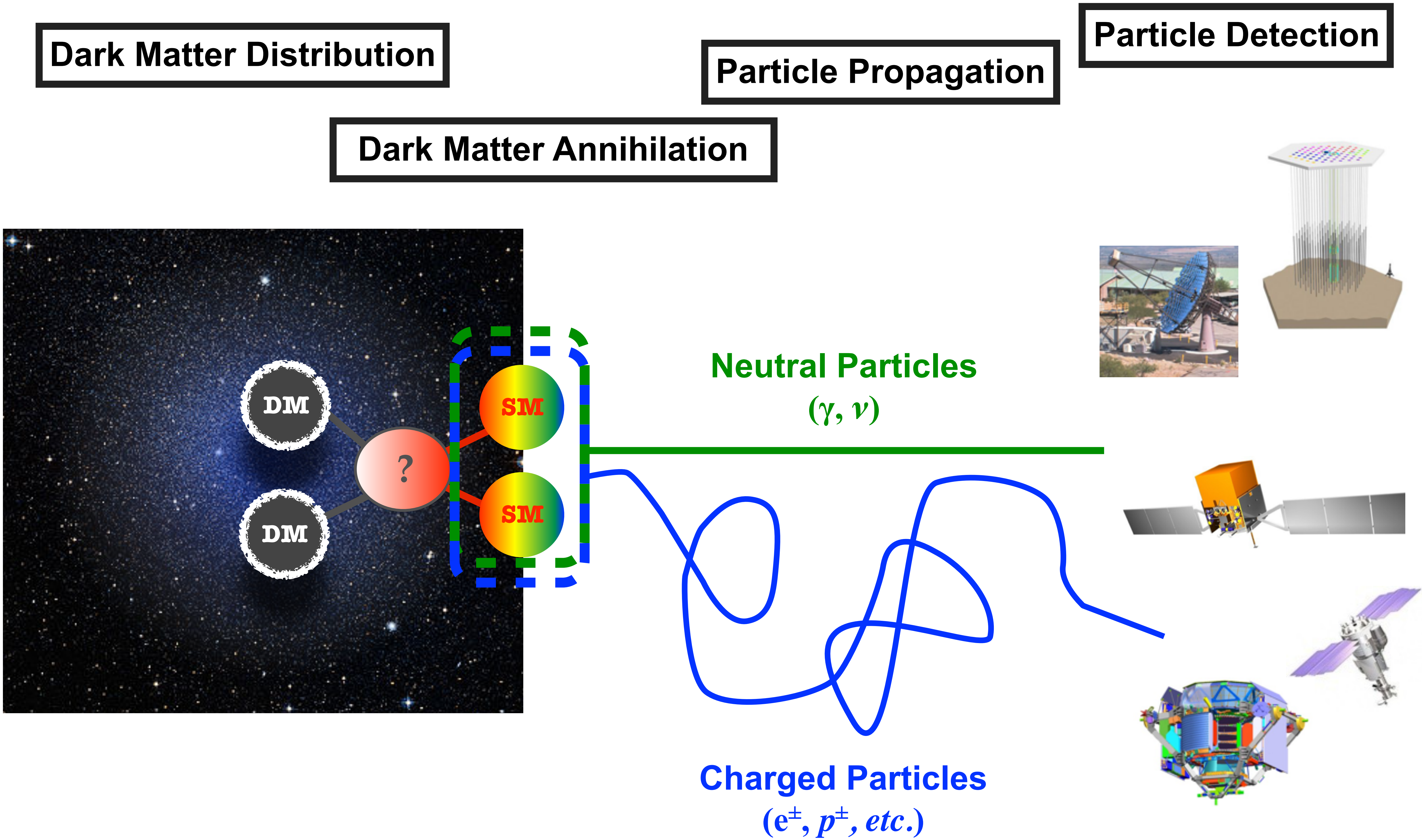
WMAP Science Team



Hunting for WIMPs



Indirect Detection



Indirect Detection

Particle Flux
(signal in data)

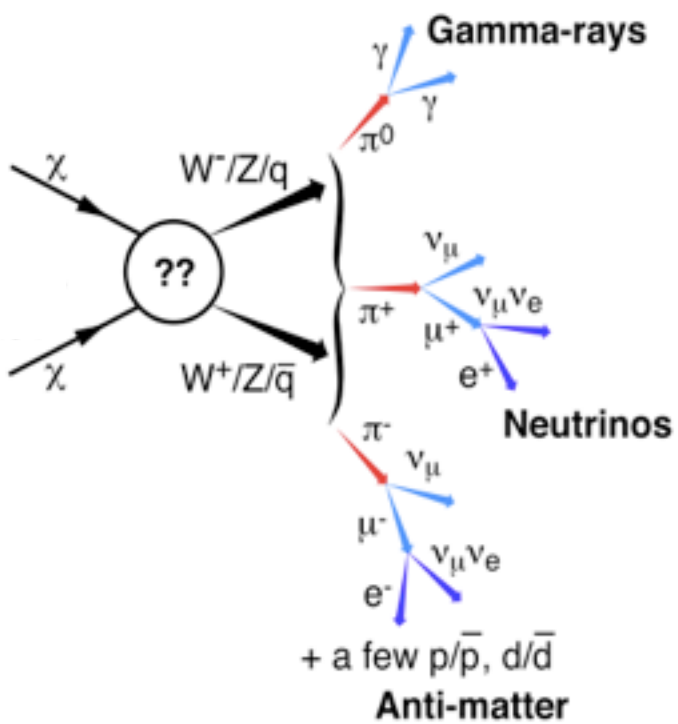
Particle Physics
(particles per annihilation)

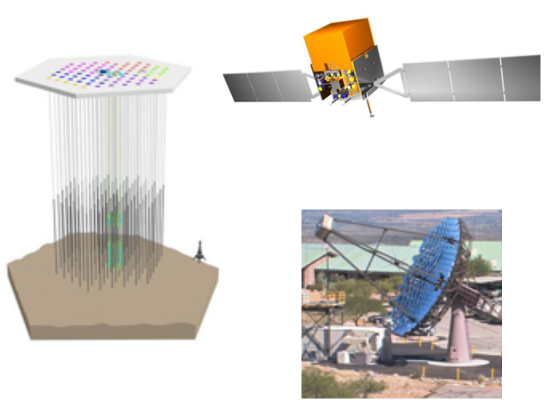
$$\frac{d\Phi}{dE}(E,\phi,\theta) = \frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f}{dE}B_f$$

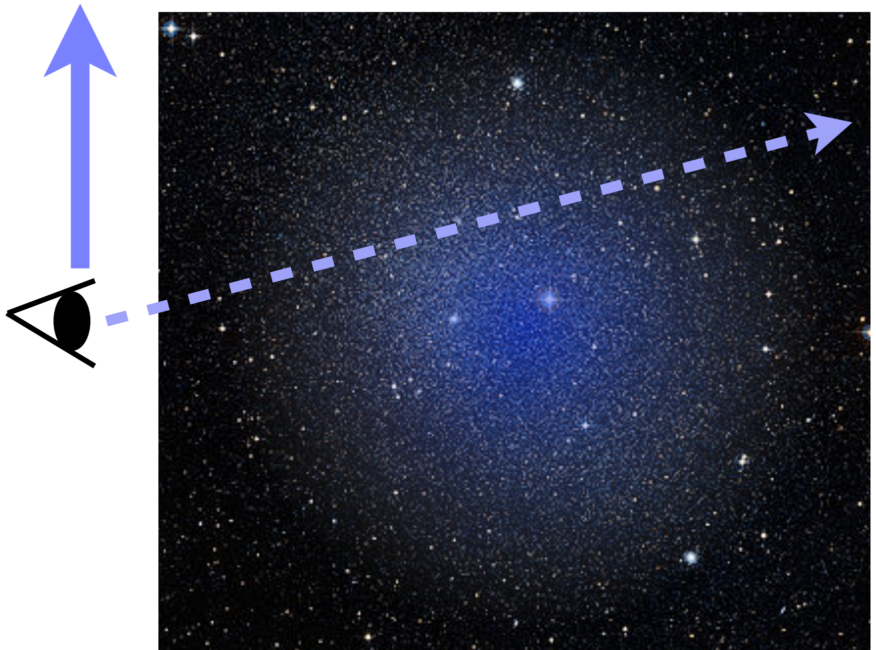
$$\times$$

$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

Dark Matter Distribution
(line-of-sight integral)



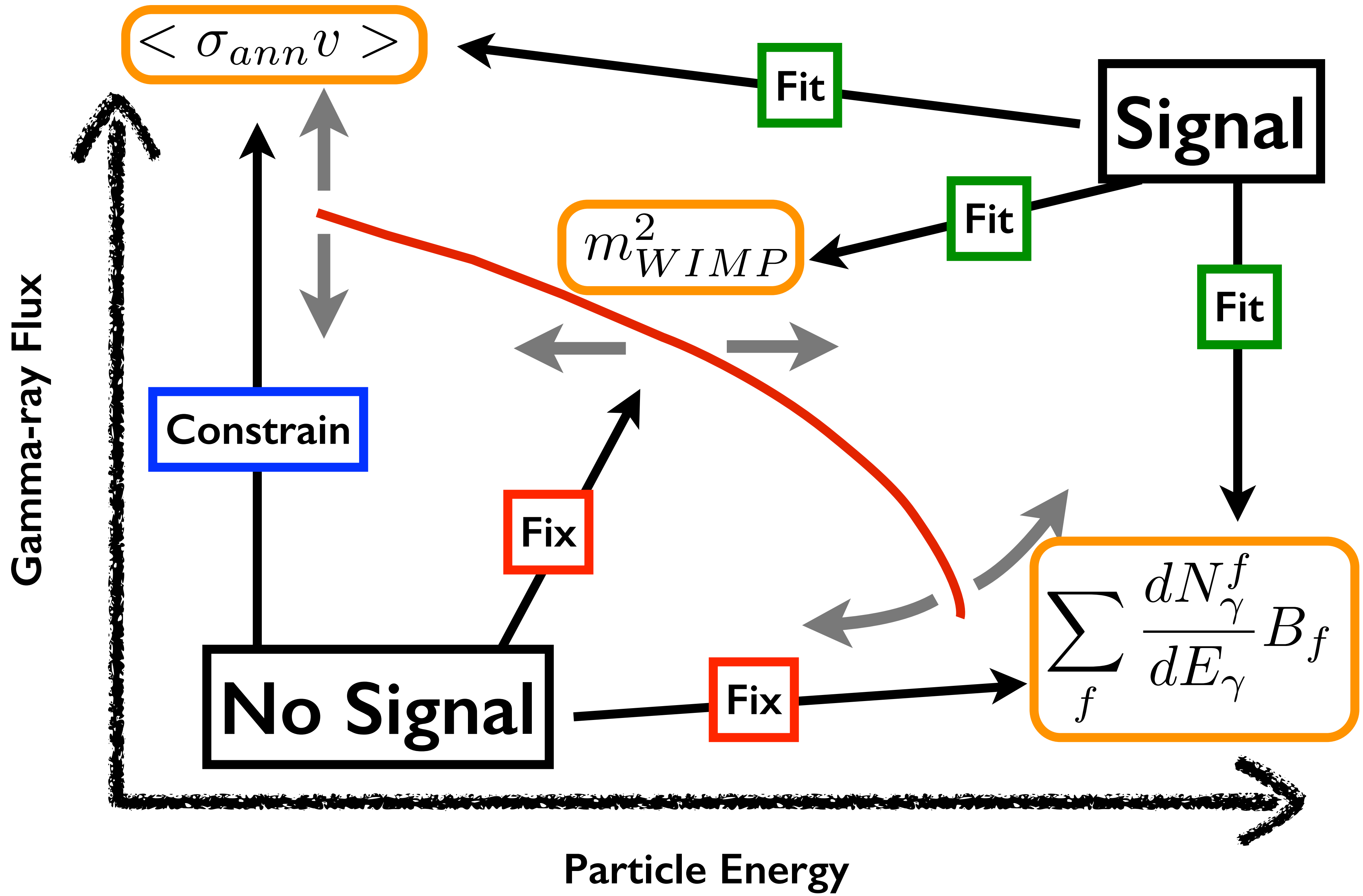




Gamma-ray Spectrum

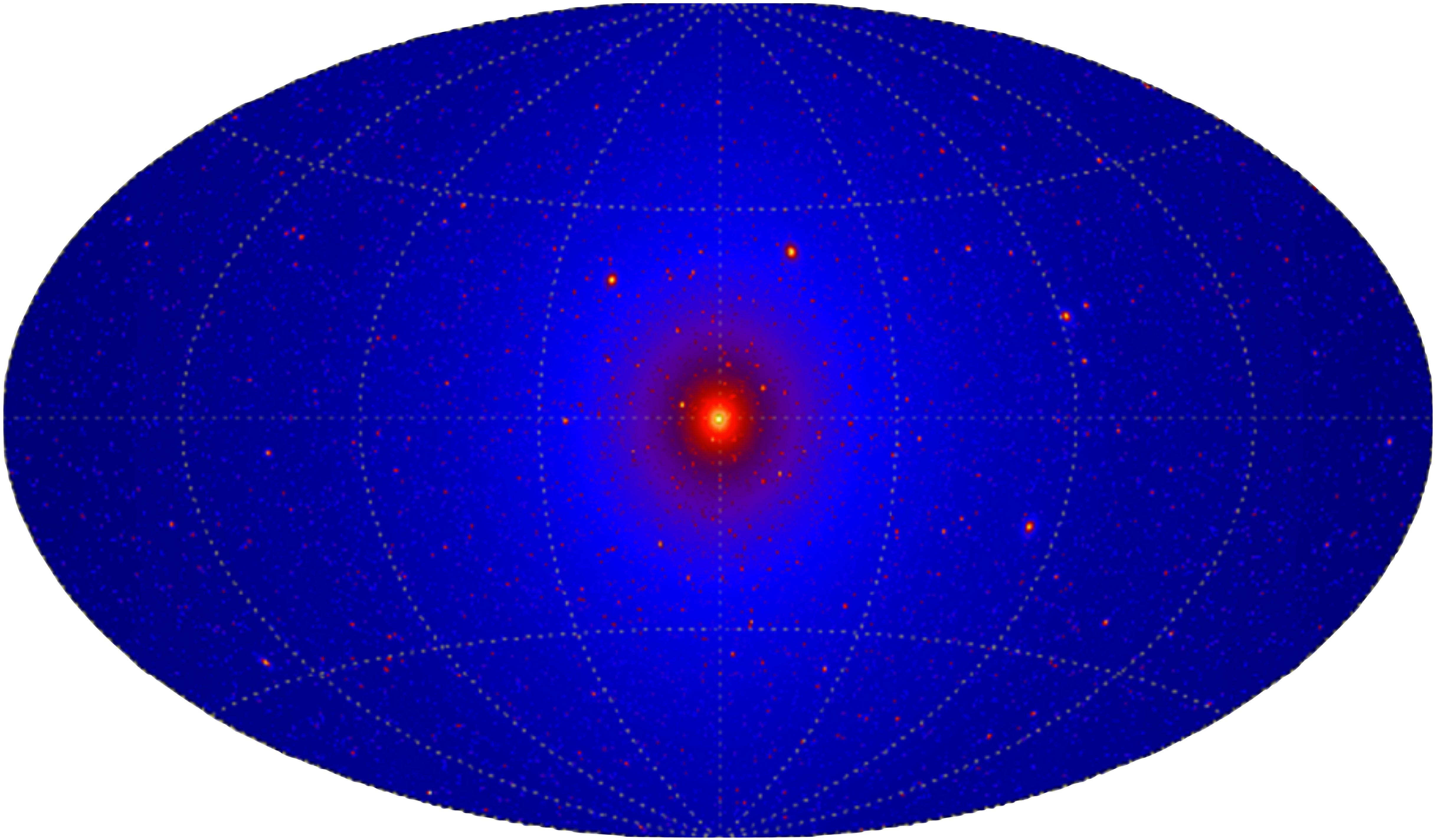
$$\langle \sigma v \rangle \sim 3 \times 10^{-26} \mathrm{cm}^3\,\mathrm{s}^{-1}$$

$$\frac{1}{4\pi} \frac{< \sigma_{ann} v >}{2 m_{WIMP}^2} \sum_f \frac{dN^f}{dE} B_f$$



Dark Matter Distribution

$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$



Piere et al. Phys Rev D83, 023581 (2011)

Dark Matter Distribution

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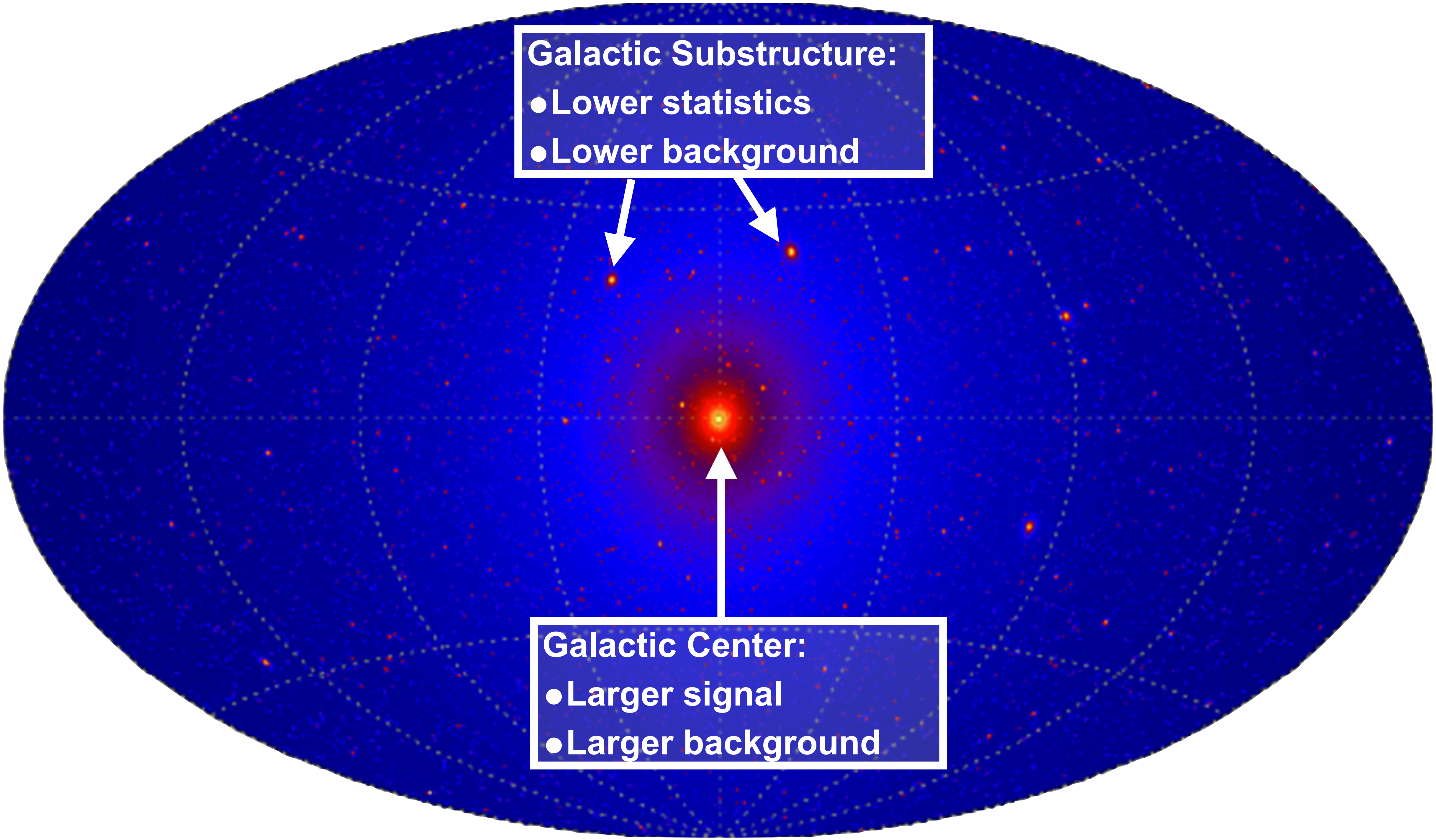
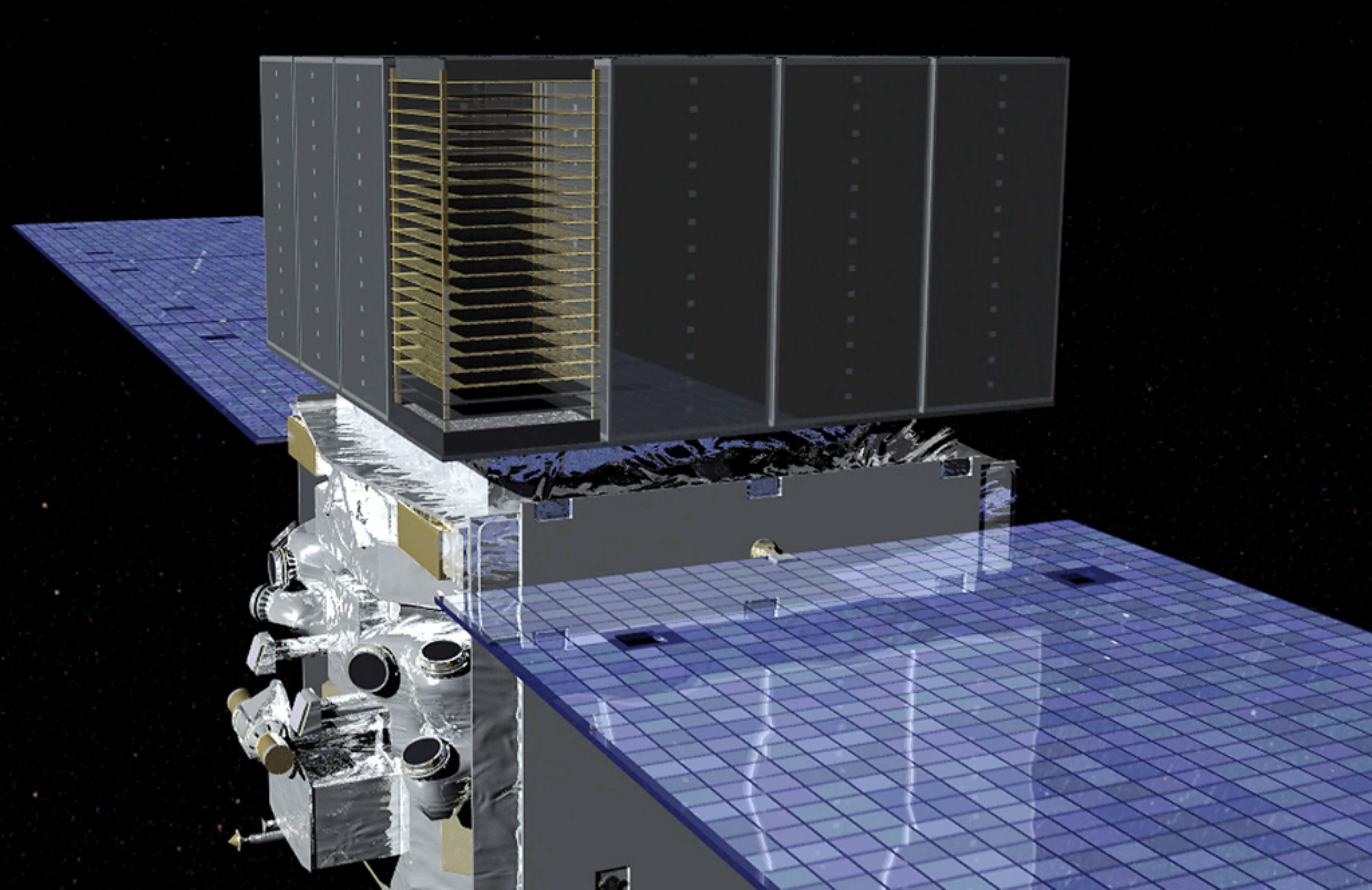


Piere et al. Phys Rev D83, 023581 (2011)

The Fermi Large Area Telescope

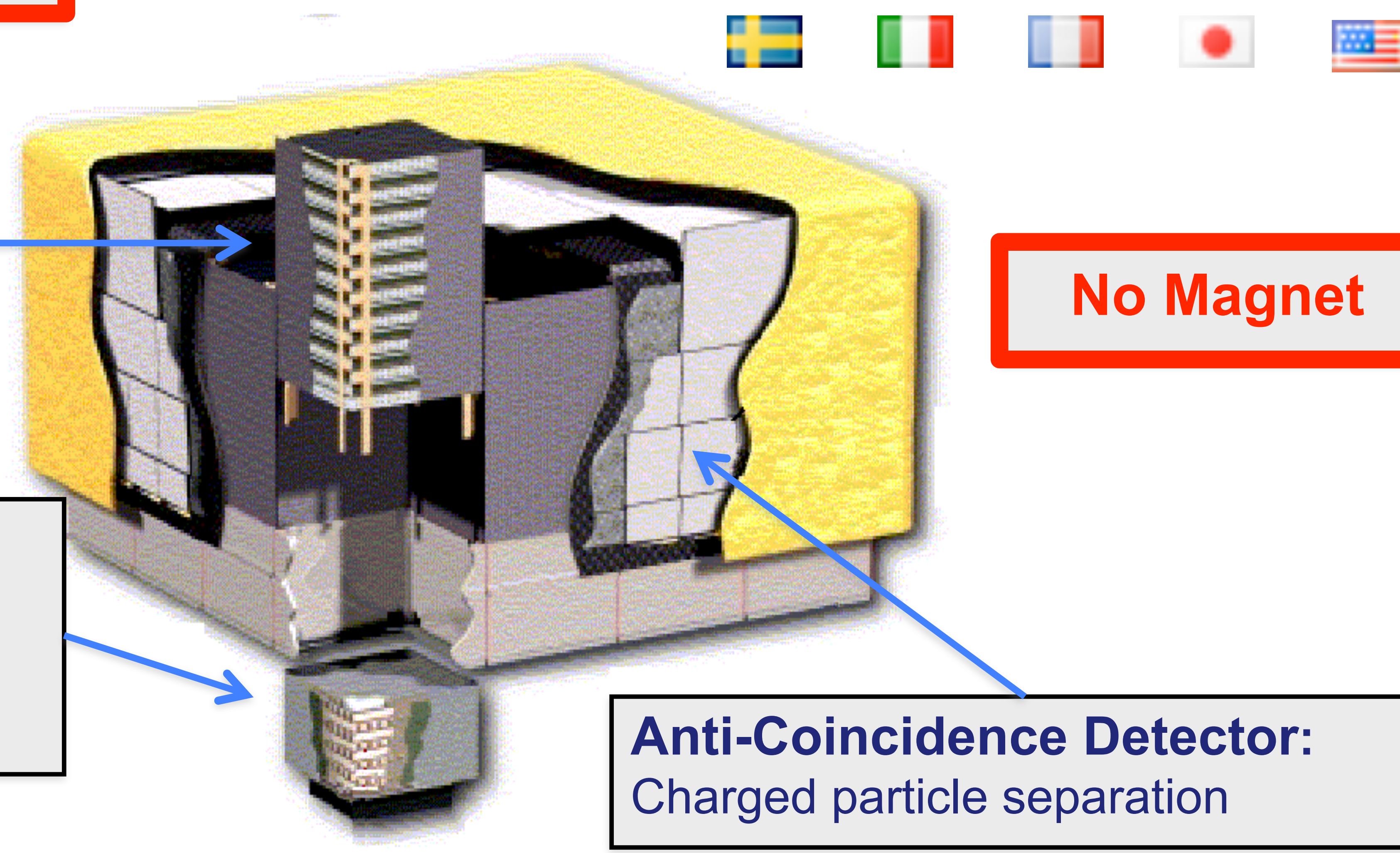
The Fermi Large Area Telescope (LAT)



The Fermi Large Area Telescope

Public Data Release:
All γ-ray data made public within 24 hours (usually less)

Fermi LAT Collaboration:
~400 Scientific Members, NASA / DOE & International Contributions



Si-Strip Tracker:
convert $\gamma \to e^+e^-$
reconstruct γ direction
EM vs. hadron separation

No Magnet

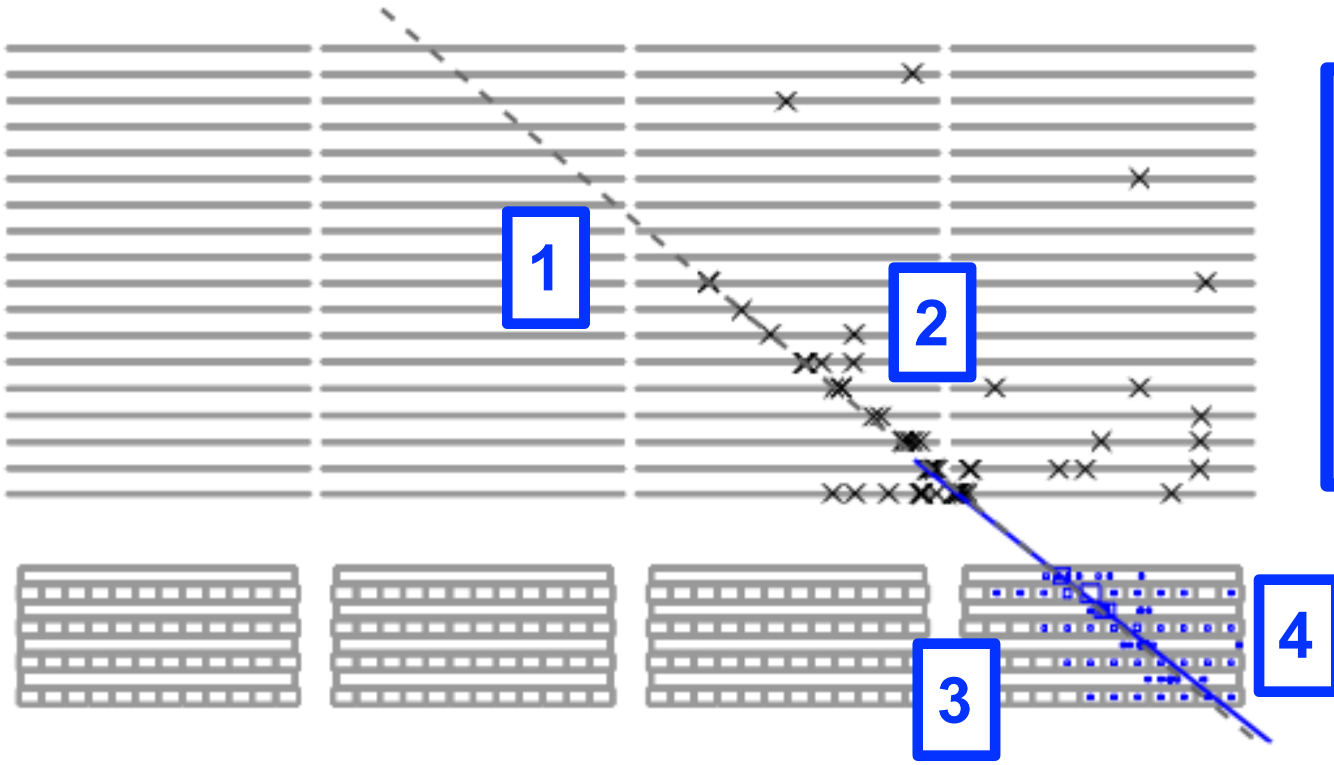
Hodoscopic CsI Calorimeter:
measure γ energy
image EM shower
EM v. hadron separation

Anti-Coincidence Detector:
Charged particle separation

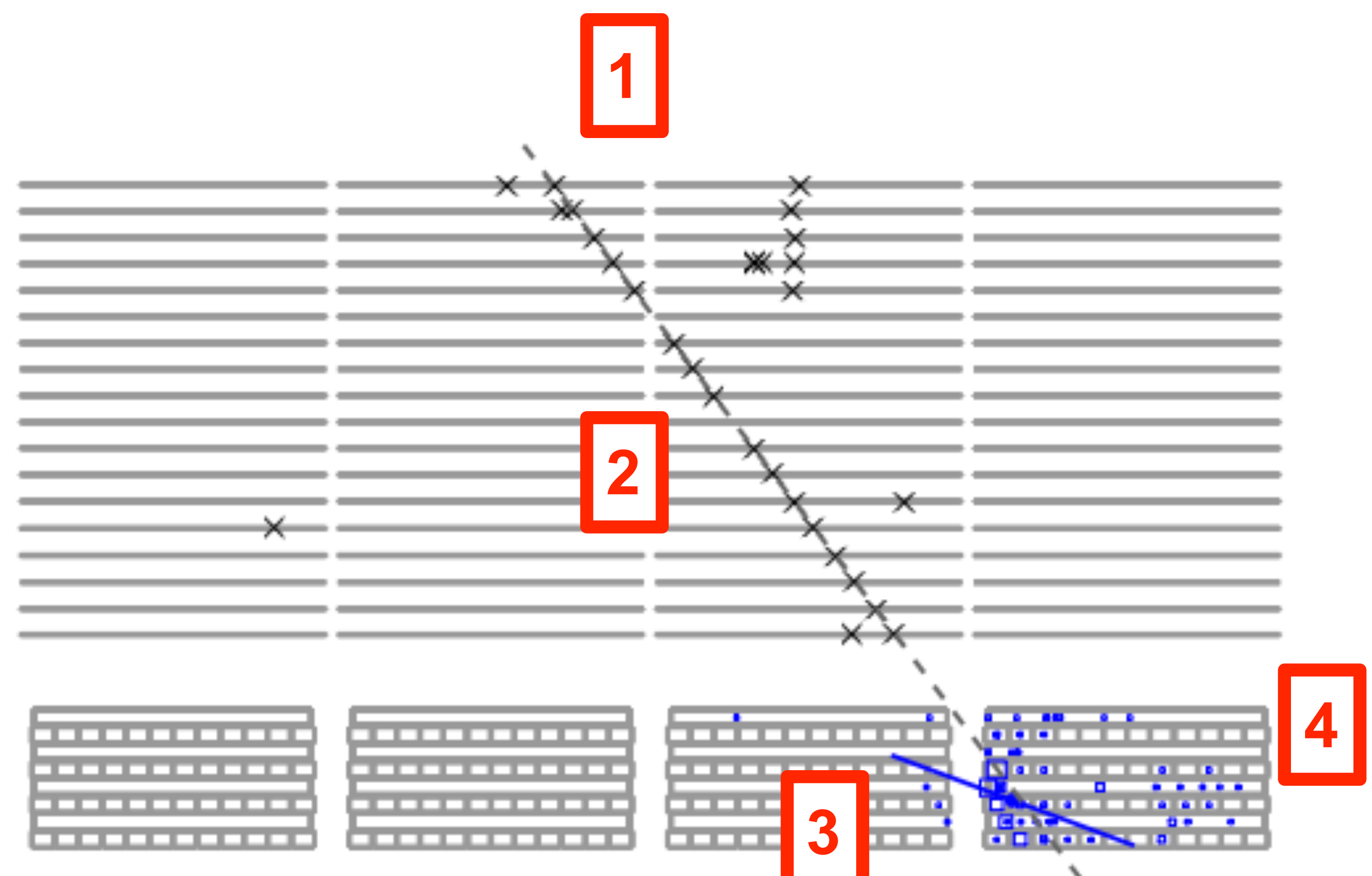
Sky Survey:
The LAT observes the whole sky every 3 hours (2.5 sr FOV)

Trigger and Filter:
Reduce data rate from ~10kHz to 300-500 Hz

Event-by-Event Detection

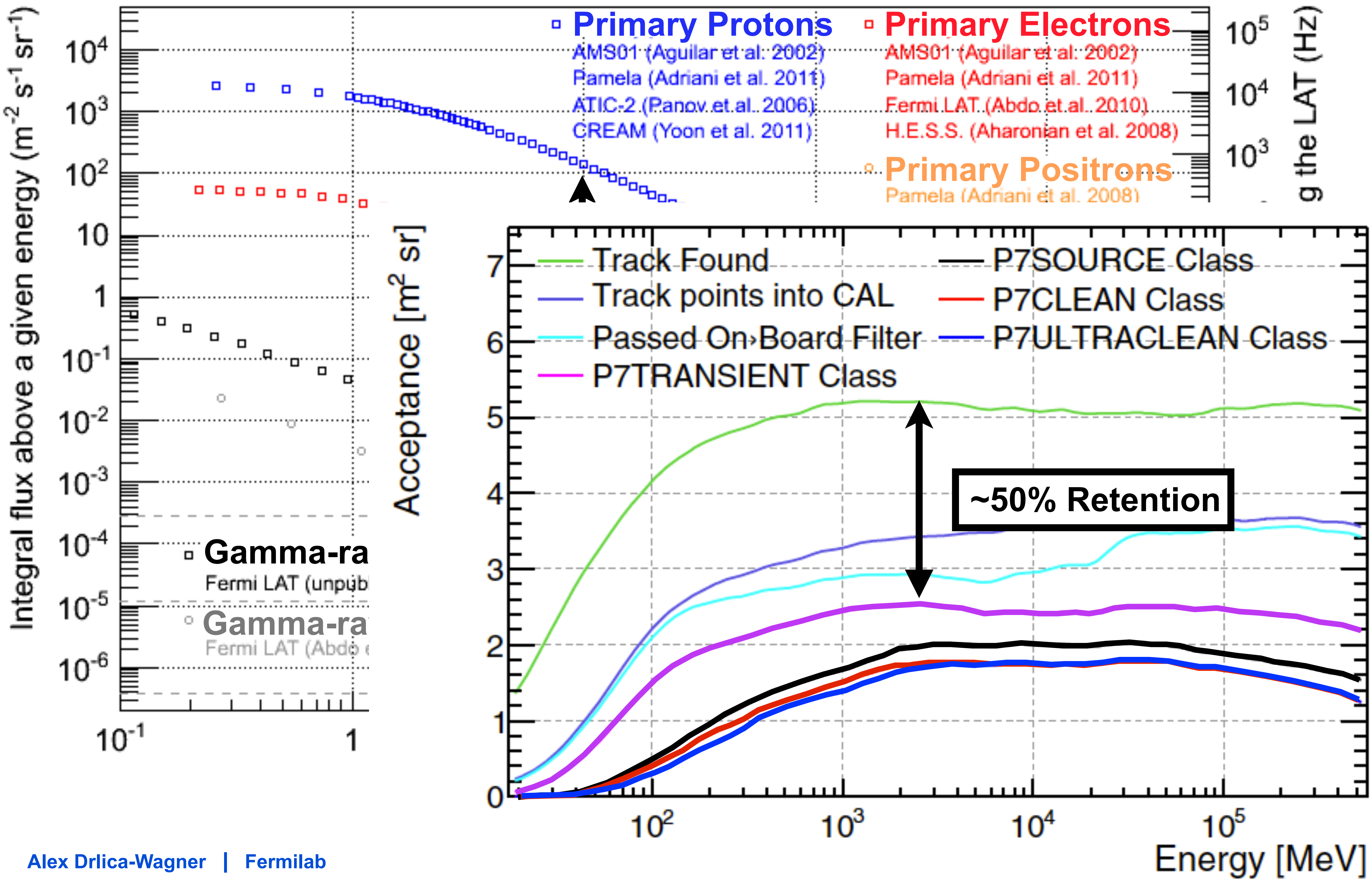


Nearly ideal γ-ray candidate:
1. Track starts in middle of TKR
2. Extra hits near track
3. CAL axis aligned with track
4. CAL energy confined near axis

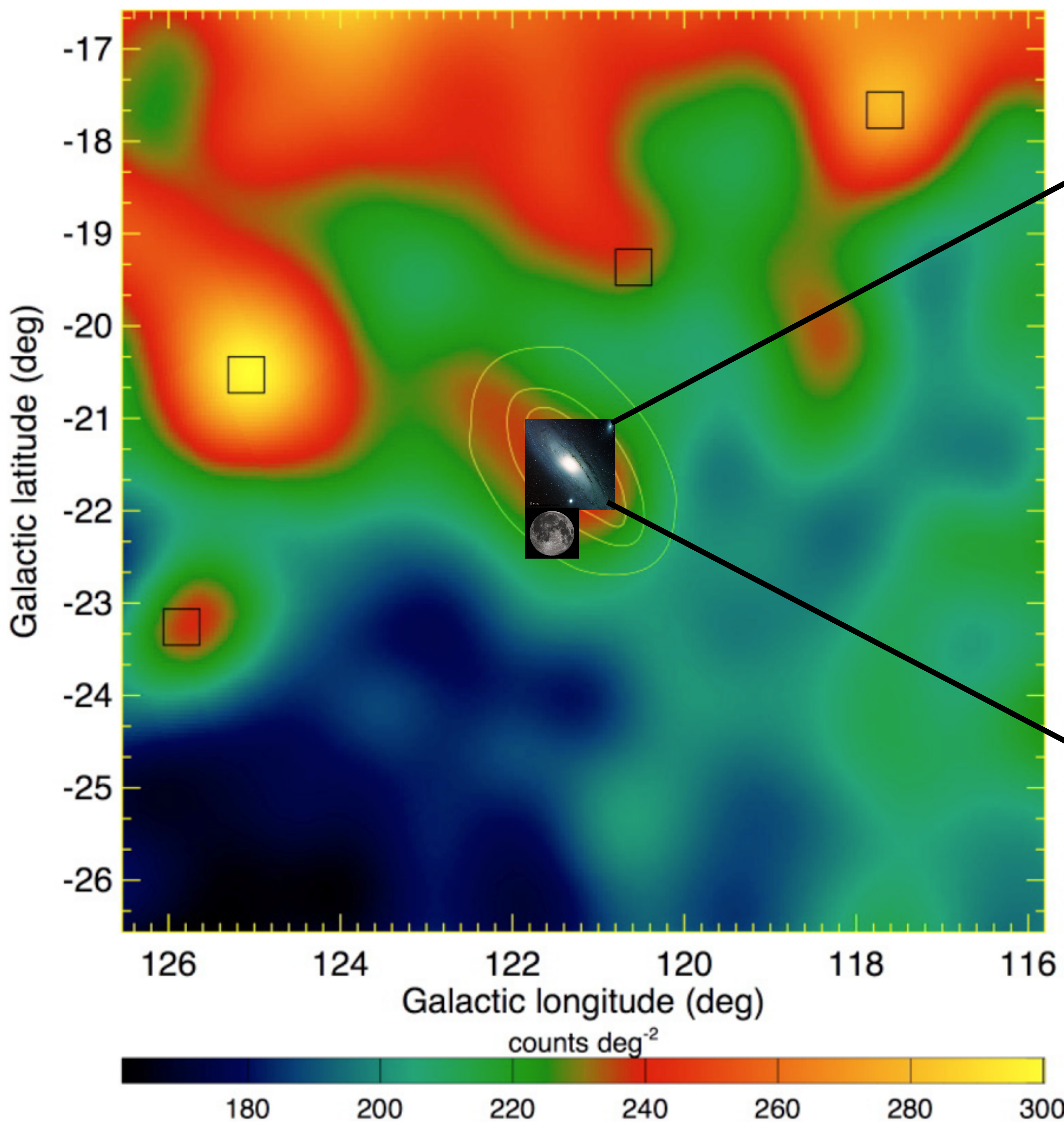


Nearly ideal proton candidate:
1. Starts at top of TKR
2. Few extra hits near track
3. CAL axis not-aligned with track
4. CAL energy “lumpier”
5. Signal in the ACD (not shown)

Background Rejection

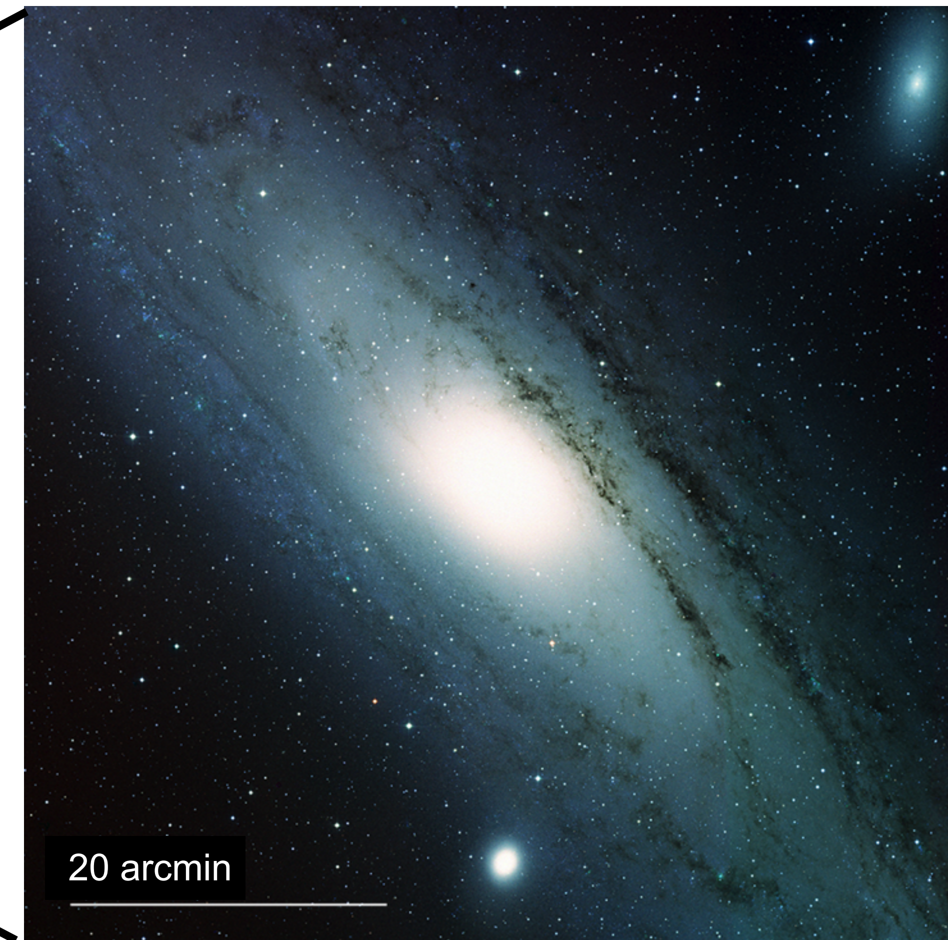


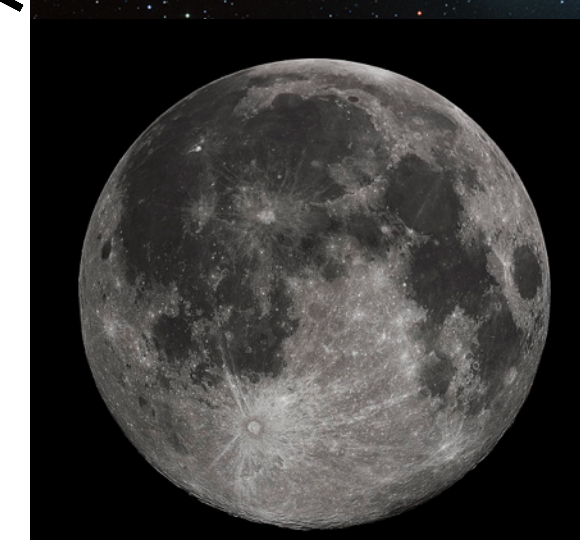
Fermi-LAT Performance



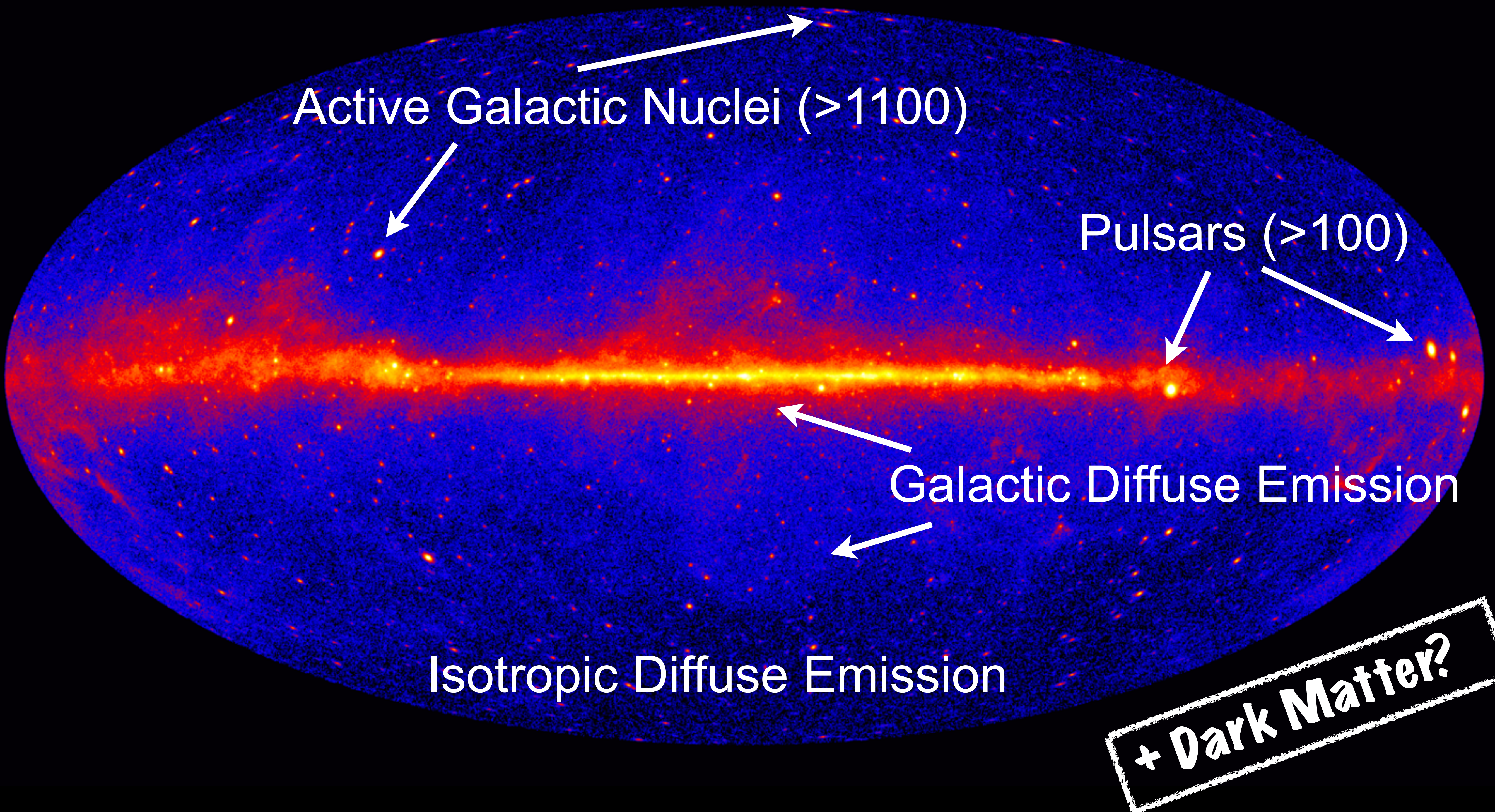
Andromeda (M31)

Optical DSS Image





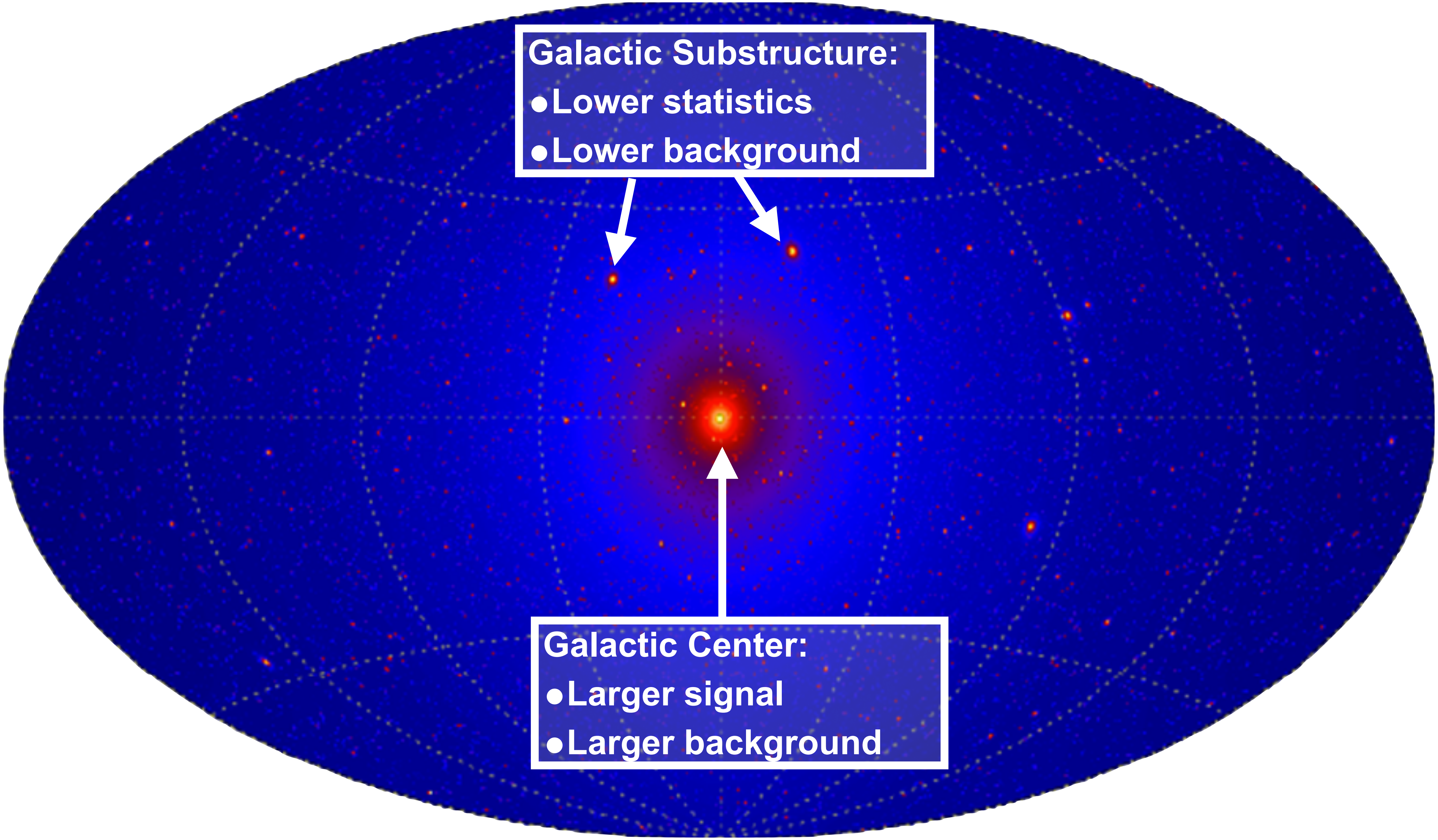
Fermi-LAT 4-Year All-Sky Map



+ Pulsar Wind Nebulae + Supernova Remnants + Globular Clusters + Starburst Galaxies + Unassociated Sources + etc.

Dark Matter Distribution

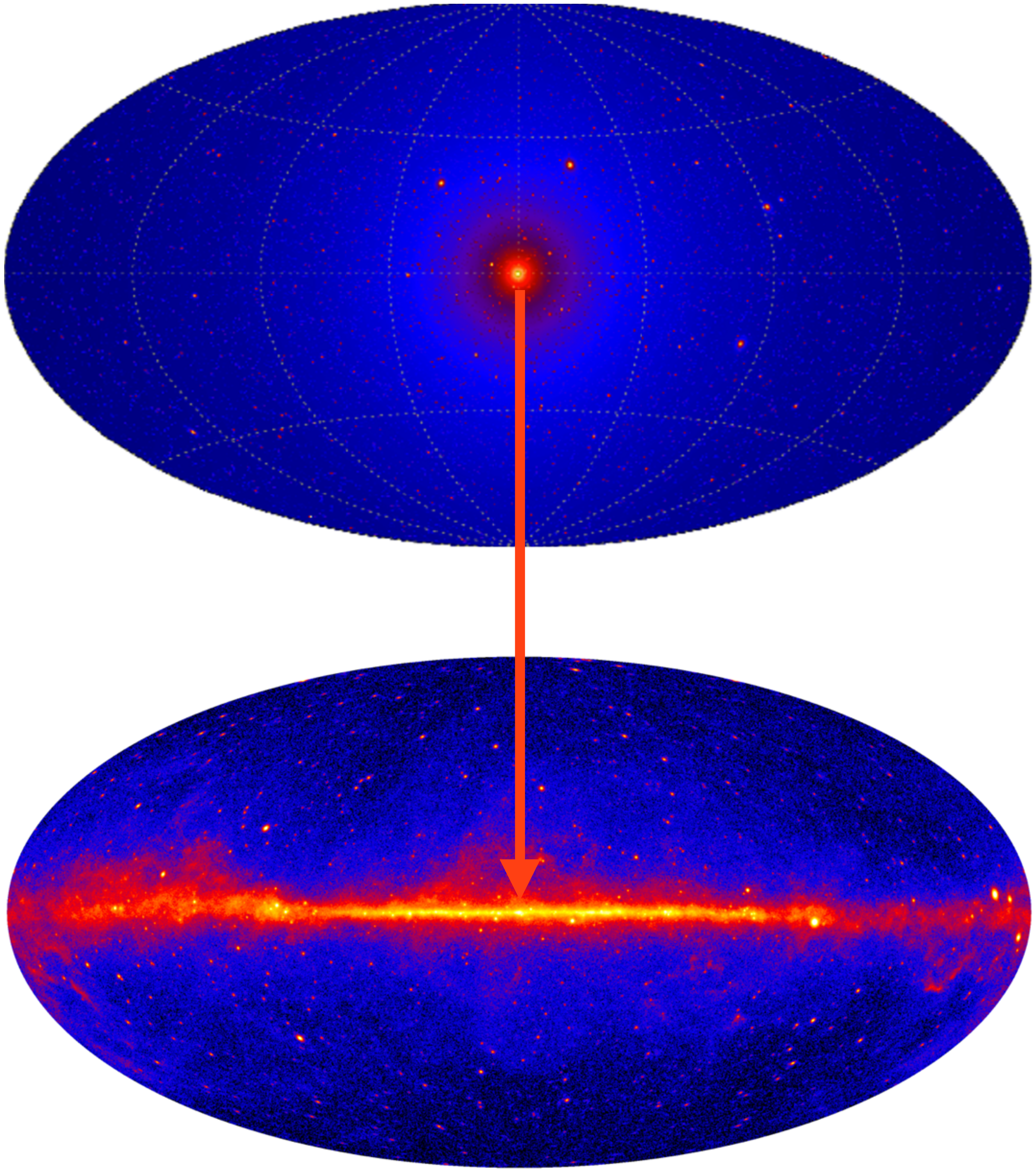
$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$



Piere et al. Phys Rev D83, 023581 (2011)

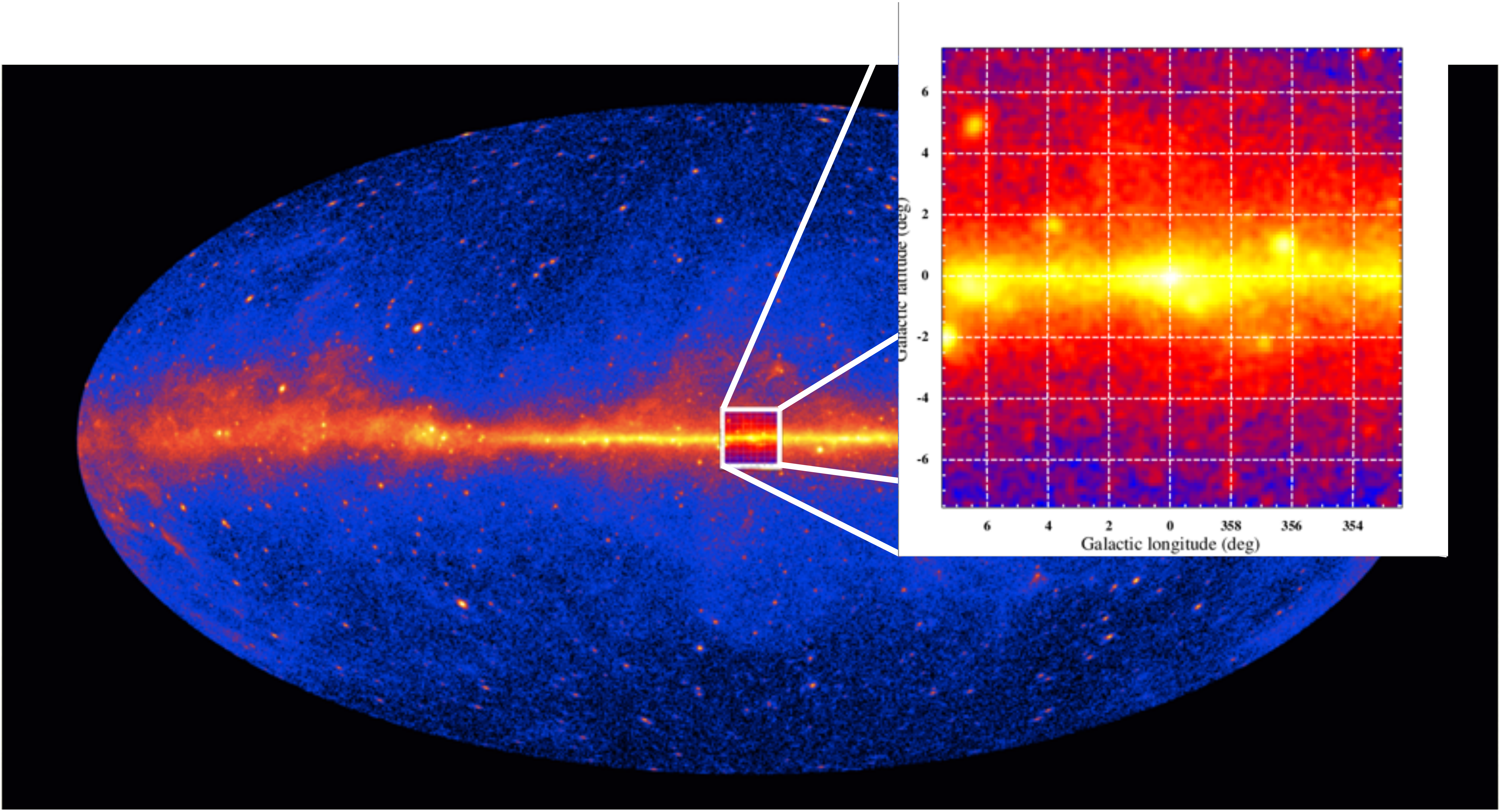
The Galactic Center

The Galactic Center



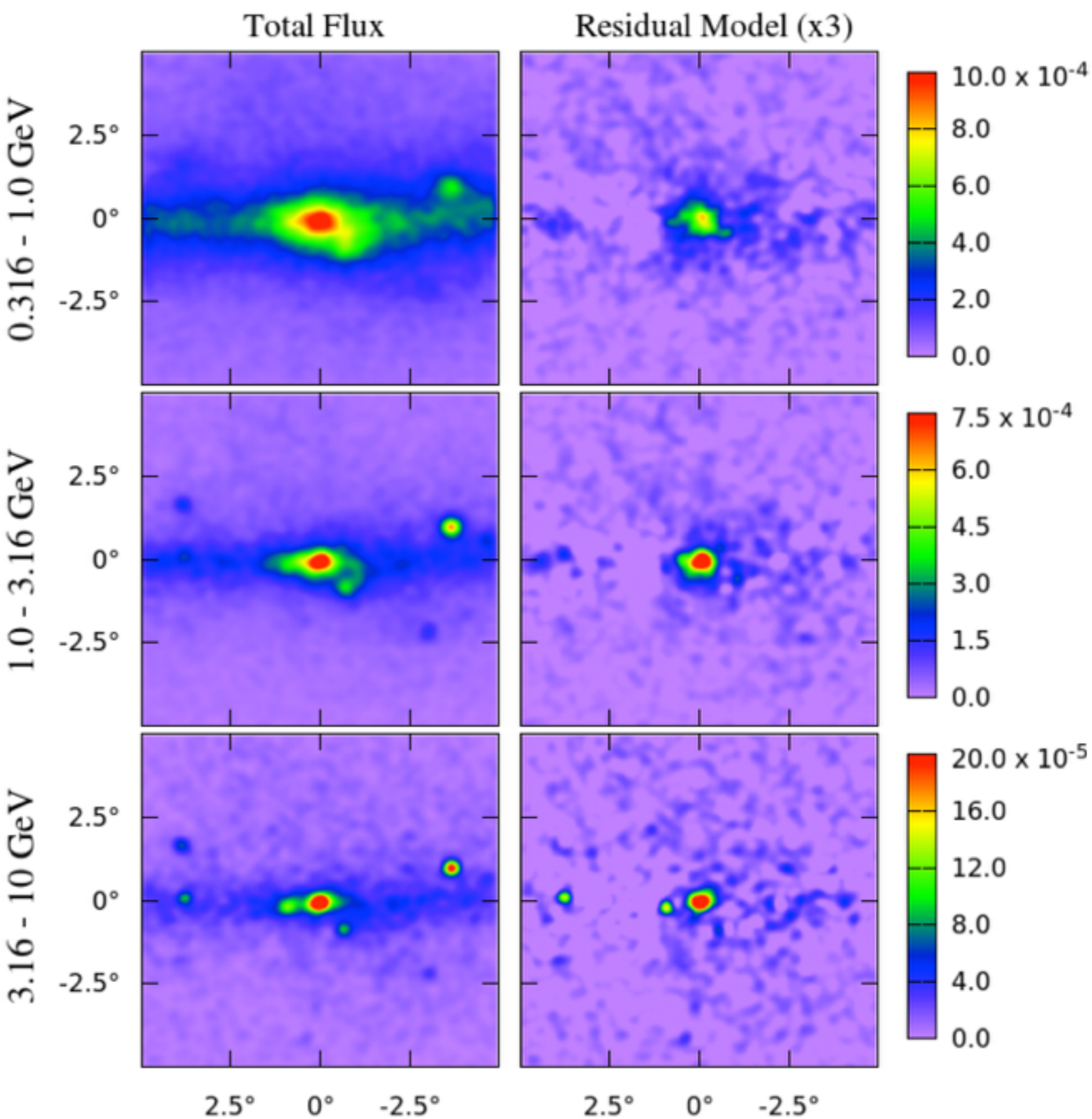
- **The Galactic Center is an appealing target for dark matter searches**
  - Deep gravitational potential
  - Relatively nearby
- **However, it is extremely complicated**
  - Diffuse emission from cosmic-ray interactions with Galactic gas and dust
  - Densely populated by astrophysical sources (e.g., pulsars, SNR)
  - Detected in other wavelengths (e.g., radio, X-ray, TeV)
- **Topic of much study…**
  - Hooper & Linden (2011)
  - Boyarski et al. (2011)
  - Abazajian & Kaplinghat (2012)
  - Huang et al. (2013)
  - Abazajian et al. (2014)
  - Daylan et al. (2014)
  - Calore et al. (2014)
  - etc.

The Galactic Center



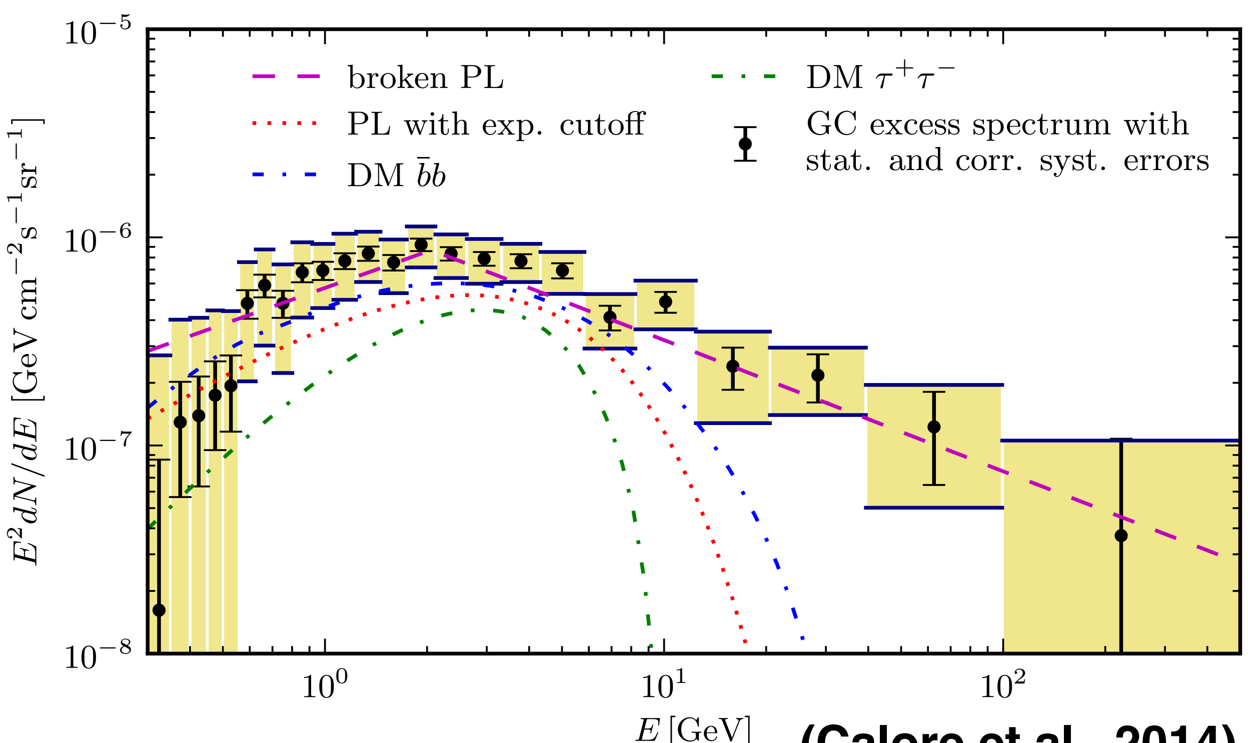
Galactic Center

Spatial Map



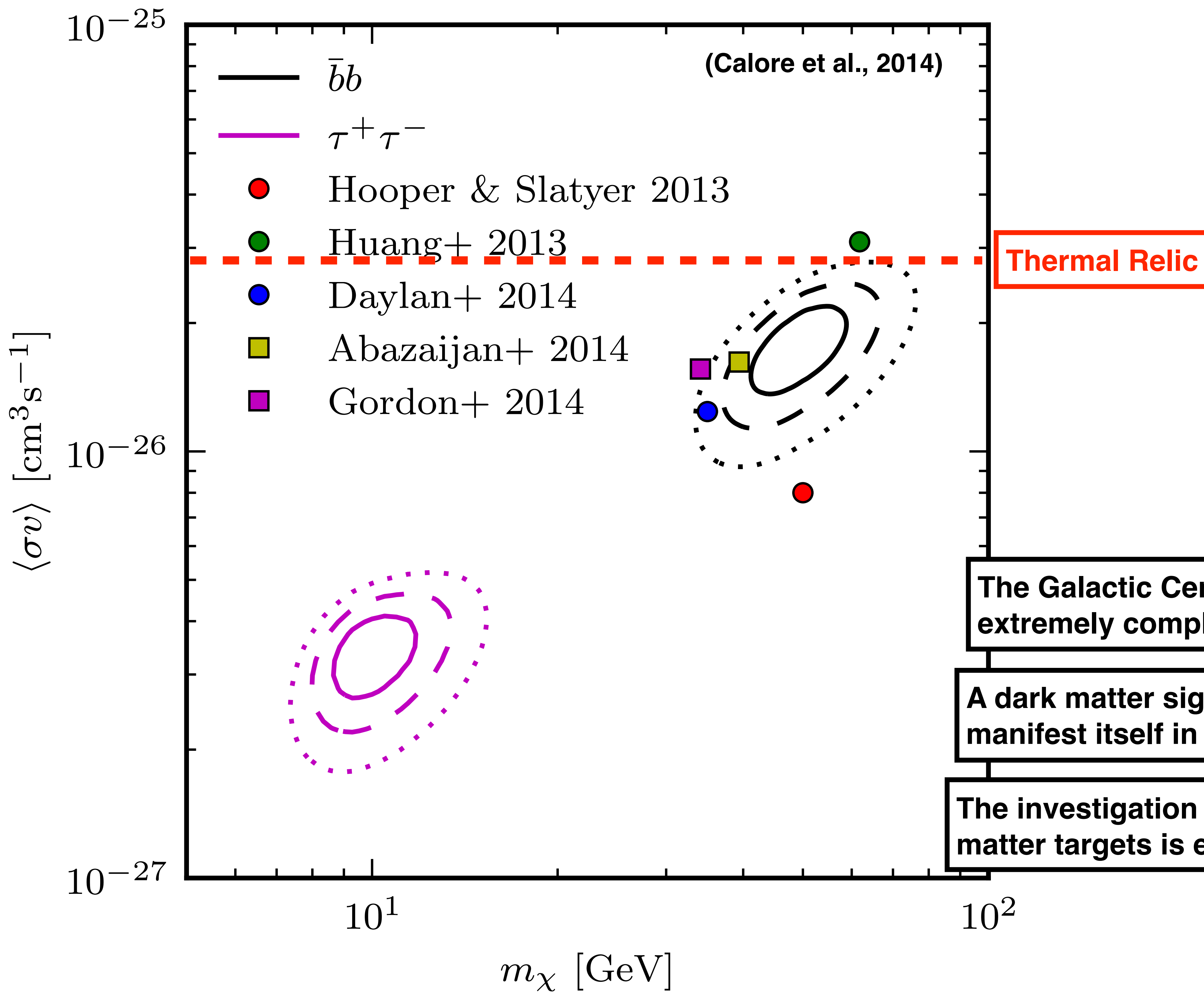
(Daylan et al., 2014)

Gamma-ray Spectrum



(Calore et al., 2014)

The Galactic Center



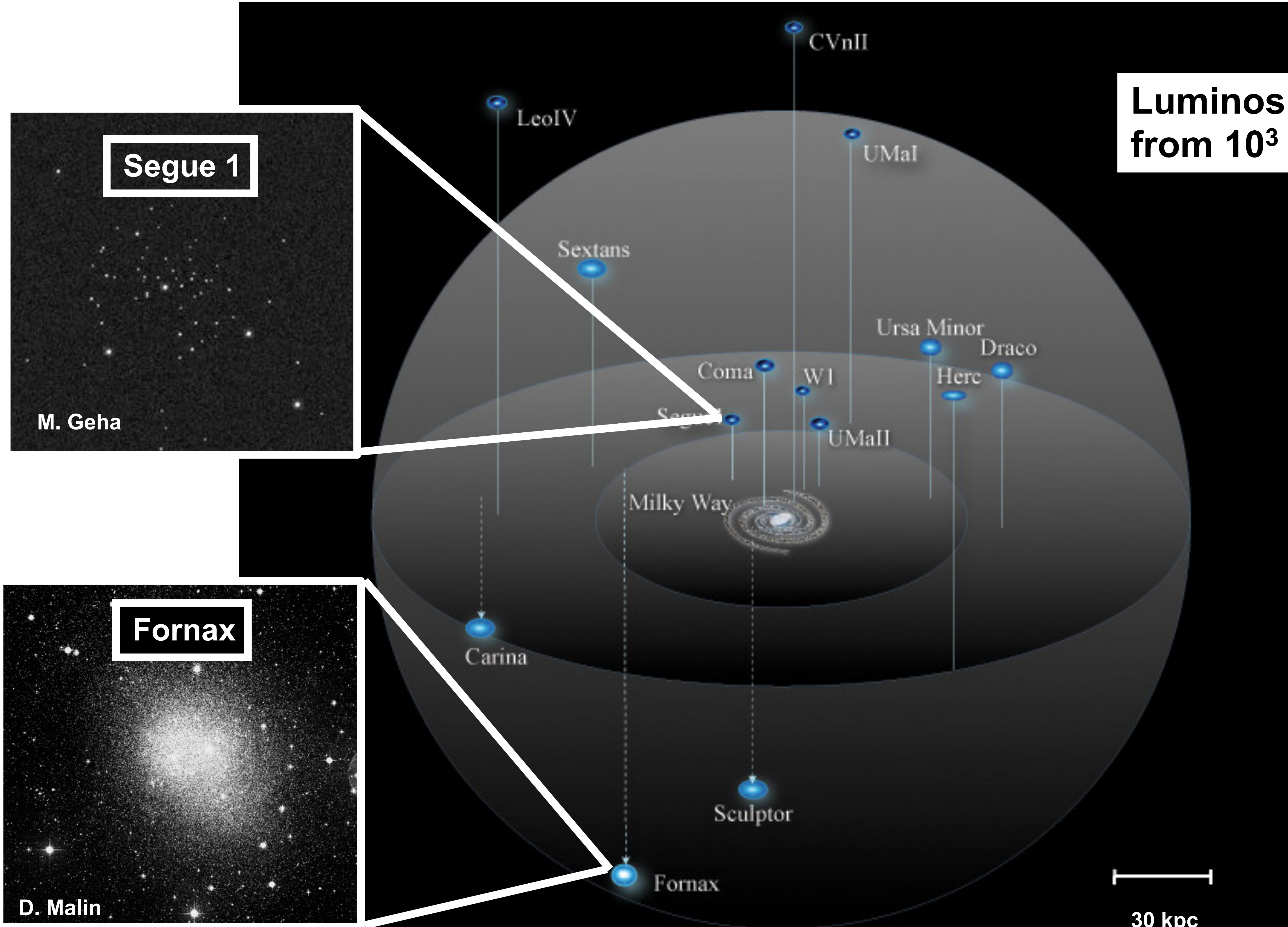
The Galactic Center is an extremely complicated region

A dark matter signal should manifest itself in other regions

The investigation of other dark matter targets is essential

Dwarf Galaxies

Dwarf Spheroidal Satellite Galaxies

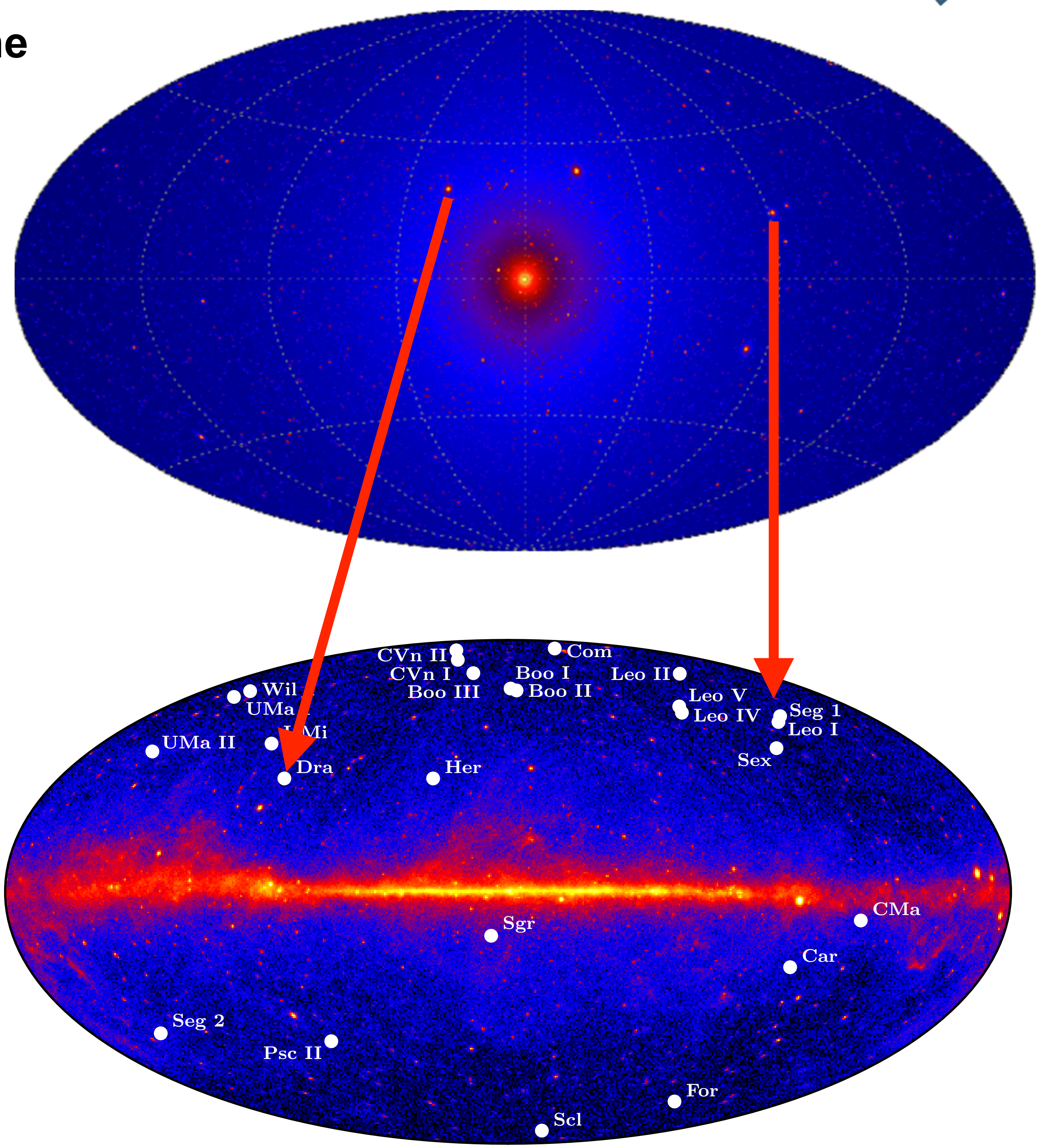


(Bullock, Geha, Powell)

Luminosities range from $10^3 L_\odot$ to $10^7 L_\odot$

Dwarf Spheroidal Galaxies

- **Most dark-matter dominated objects in the universe (100 - 1000 times more dark matter than visible matter)**
- **Relatively nearby (25 - 150 kpc)**
- **High galactic latitudes (minimize astrophysical foregrounds)**
- **Multi-wavelength observations show no evidence for astrophysical gamma-ray production**
  - **No active star formation (no energy injection)**
  - **No appreciable magnetic fields (no acceleration)**
  - **No no gas or dust (no target material)**

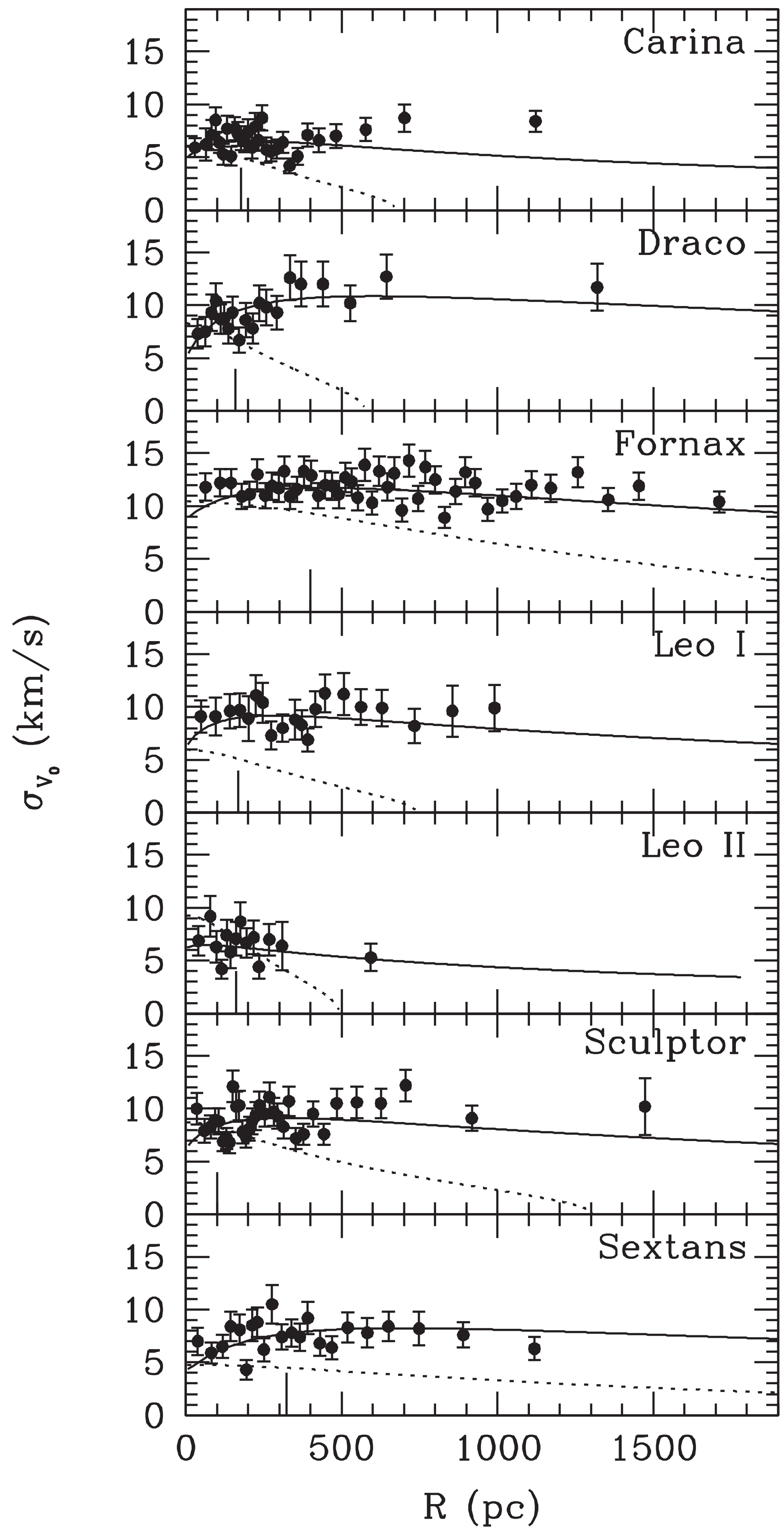


Dark Matter Content

$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

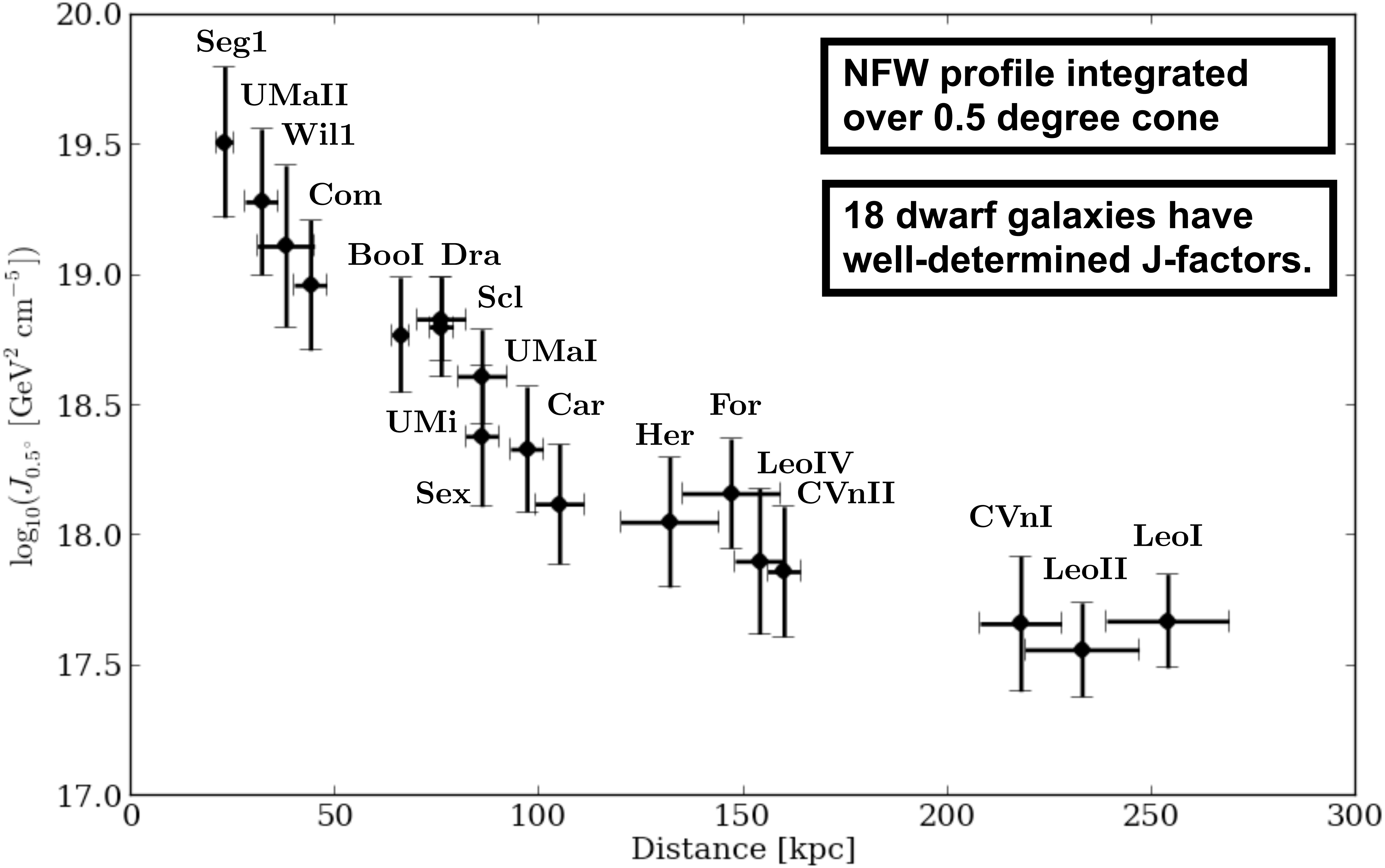
- **Dark matter content determined spectroscopically from stellar velocity dispersion**
  - **Classical dwarfs: spectra for several thousand stars**
  - **Ultra-faint dwarfs: spectra for fewer than 100 stars**
- **Assume a DM density profile to calculate a J-factor (Martinez, 2013)**
  - **Minimize J-factor uncertainty by enclosing the half-light radius**
  - **Become insensitive to the inner profile behavior (core vs. cusp) at large enough radii**
- **Include the statistical uncertainty in the J-factor in gamma-ray analysis**

Walker et al. 2007



J-Factors for 18 Dwarf Galaxies

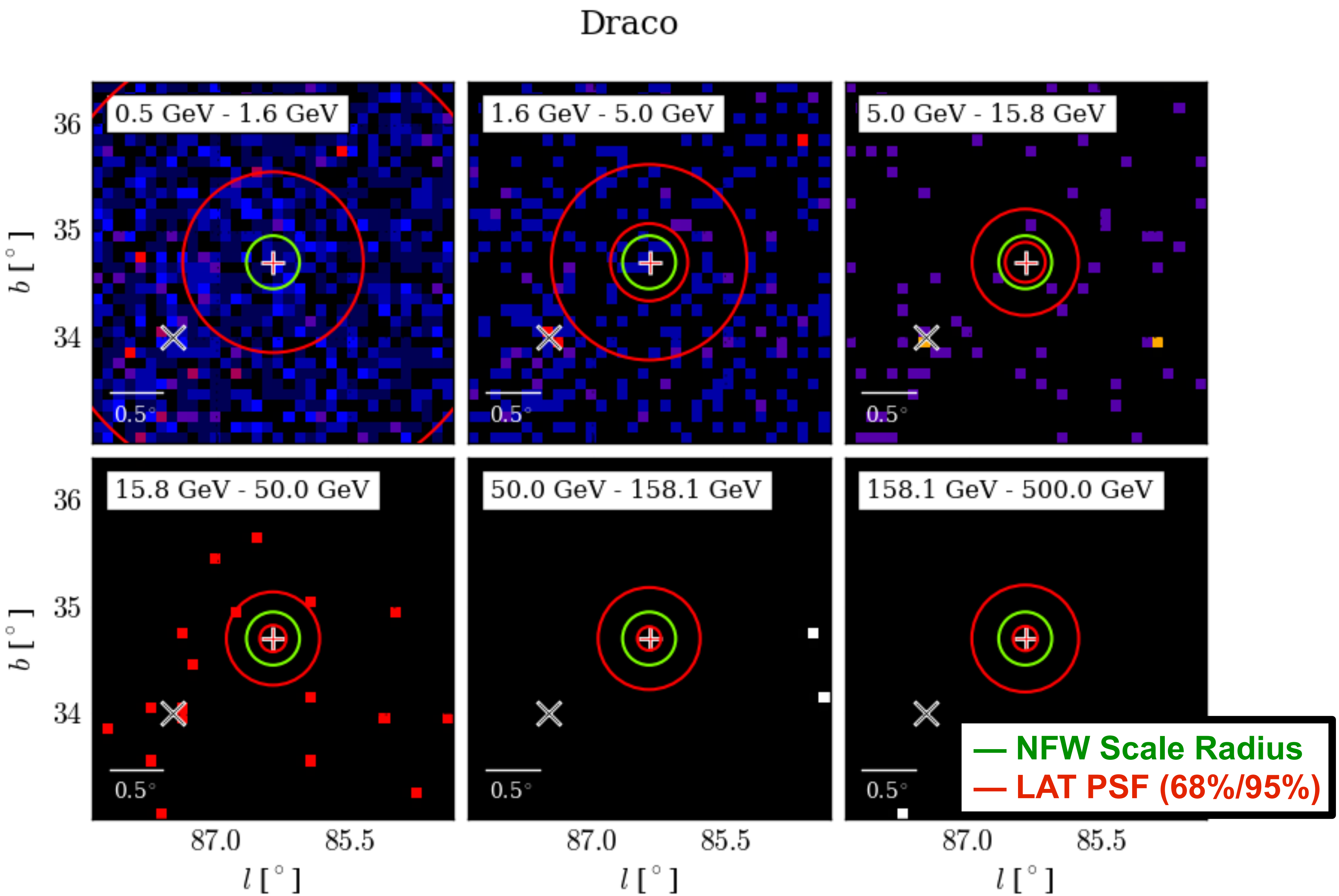
$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$



NFW profile integrated over 0.5 degree cone

18 dwarf galaxies have well-determined J-factors.

Gamma-ray Count Maps



Joint Likelihood Analysis

- Assume same dark matter particle present in all dwarf spheroidal galaxies (same spectrum)
- Use all dwarf galaxies with well-determined J-factors in non-overlapping regions (N=15)
- Perform a combined likelihood analysis:
  - Predicted flux for each dwarf will depend on individual dark matter content (J-factor)
  - Include statistical uncertainties from stellar kinematic data.
  - Fit backgrounds independently
- Joint likelihood function:

$$\frac{d\Phi}{dE}(E,\phi,\theta) = \frac{1}{4\pi}\frac{\langle\sigma_{ann}v\rangle}{2m_{\rm DM}^2}\sum_f \frac{dN^f}{dE}B_f \times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

$$L(D\,|\,\underbrace{\mathbf{p_m}}_{\text{Shared by all dwarfs}},\underbrace{\{\mathbf{p_k}\}}_{\text{Fit for each dwarf}}) = \prod_k L_k^{\rm LAT}(D_k\,|\,\mathbf{p_m},\mathbf{p_k}) \times \underbrace{\frac{1}{\ln(10)J_k\sqrt{2\pi}\sigma_k}e^{-(\log_{10}(J_k)-\overline{\log_{10}(J_k)})^2/2\sigma_k^2}}_{\text{Uncertainty in J-factor}}$$

Shared by all dwarfs
(dark matter particle parameters)

Fit for each dwarf
(background sources)

Uncertainty in J-factor

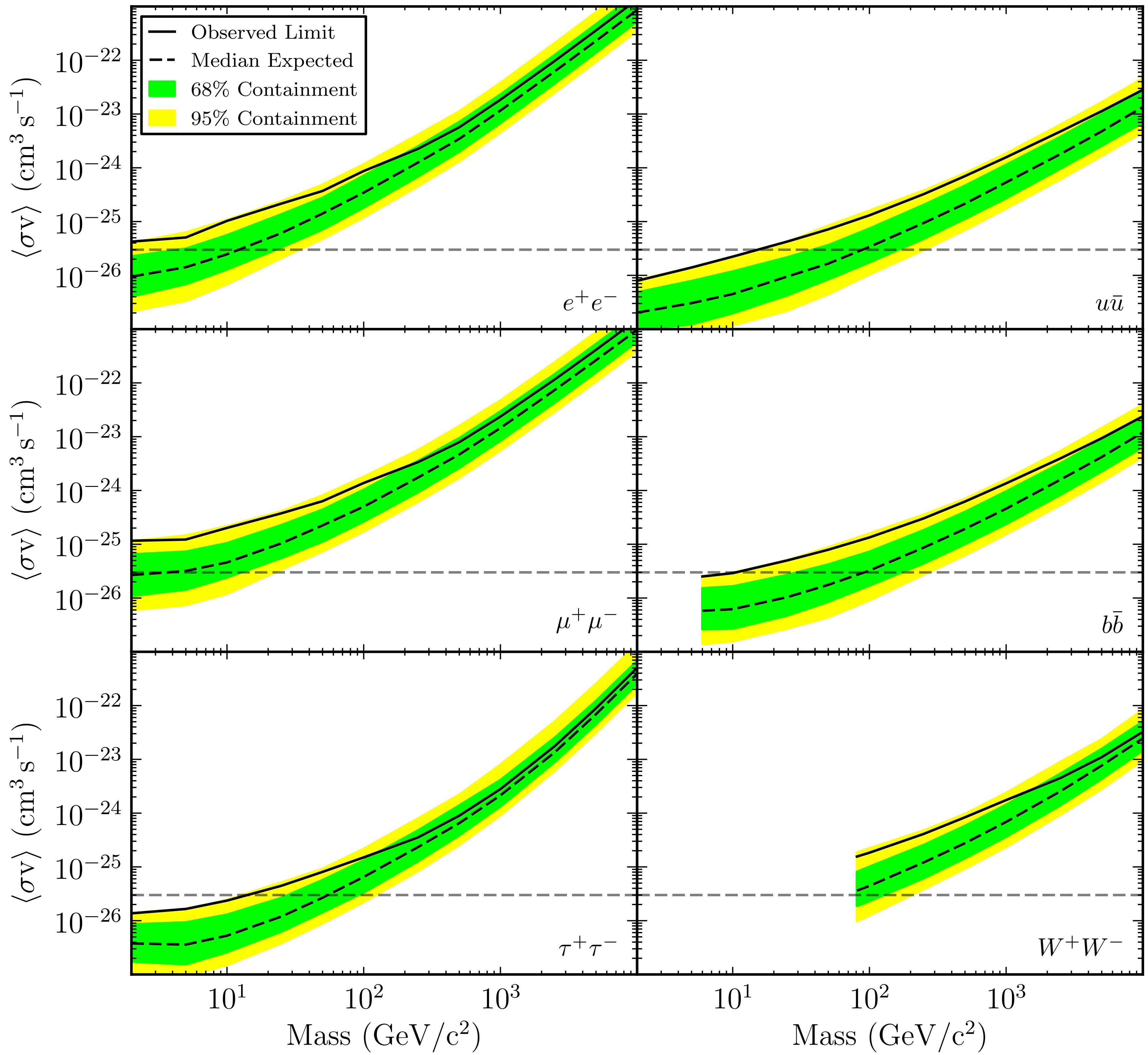
Combined Limits at 95%CL

Combine 15 dSphs

Expected sensitivity calculated from the data

- **300 sets of 15 random sky locations**
- **High-Galactic-latitude (|b|>20)**
- **>1° from LAT catalog sources**

Largest excess for 25 GeV WIMP to $b\bar{b}$, TS = 8.7 (TS > 25 threshold)



Ackermann et al. PRD 89 042001 (2014)

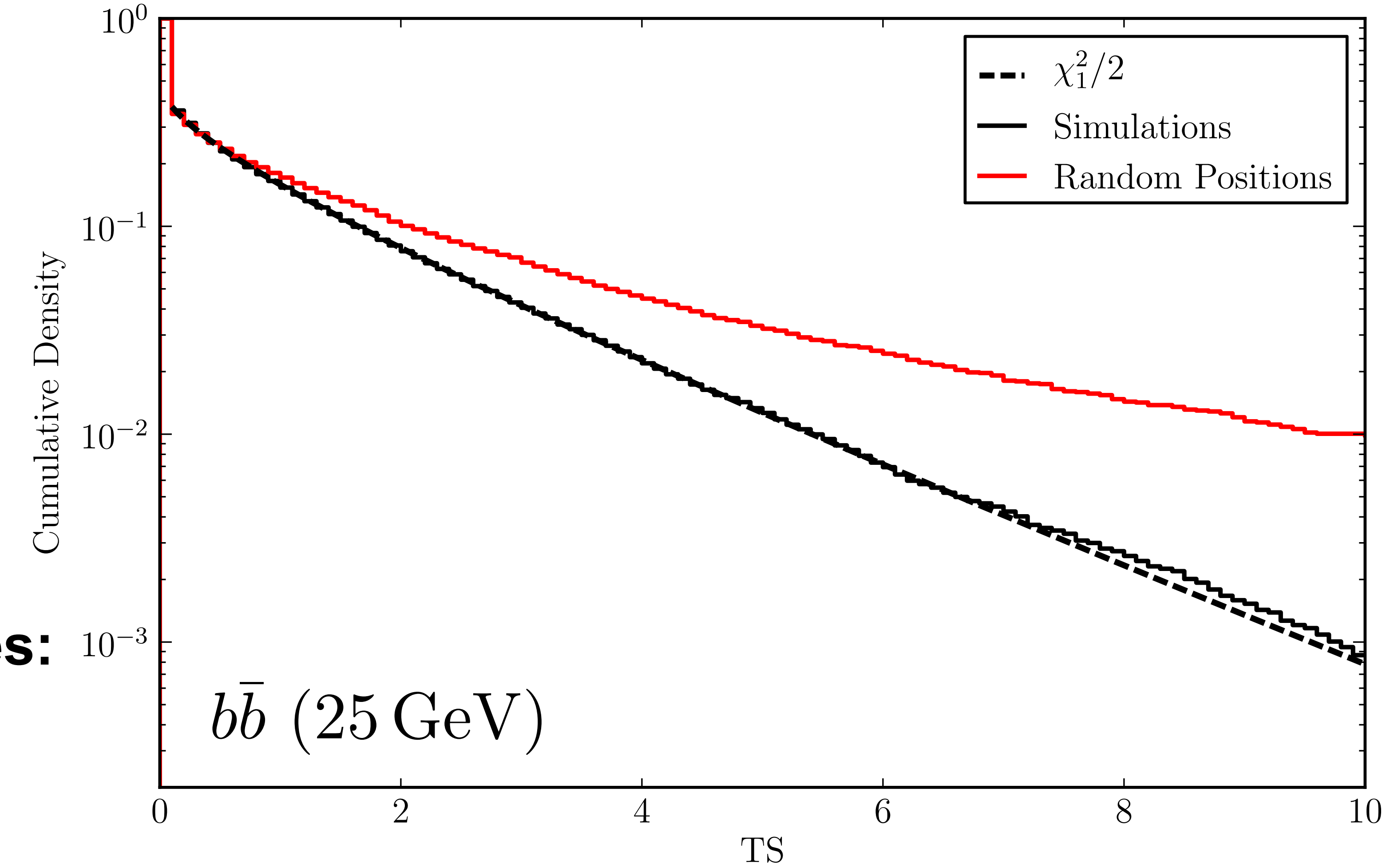
Statistical and Systematic Effects

- **Distribution of TS values in the data does not follow asymptotic theorems**

- **Confounding features of the data:**
  - **Unresolved background sources**
  - **Instrumental features**
  - **Imperfect modeling of the diffuse background**

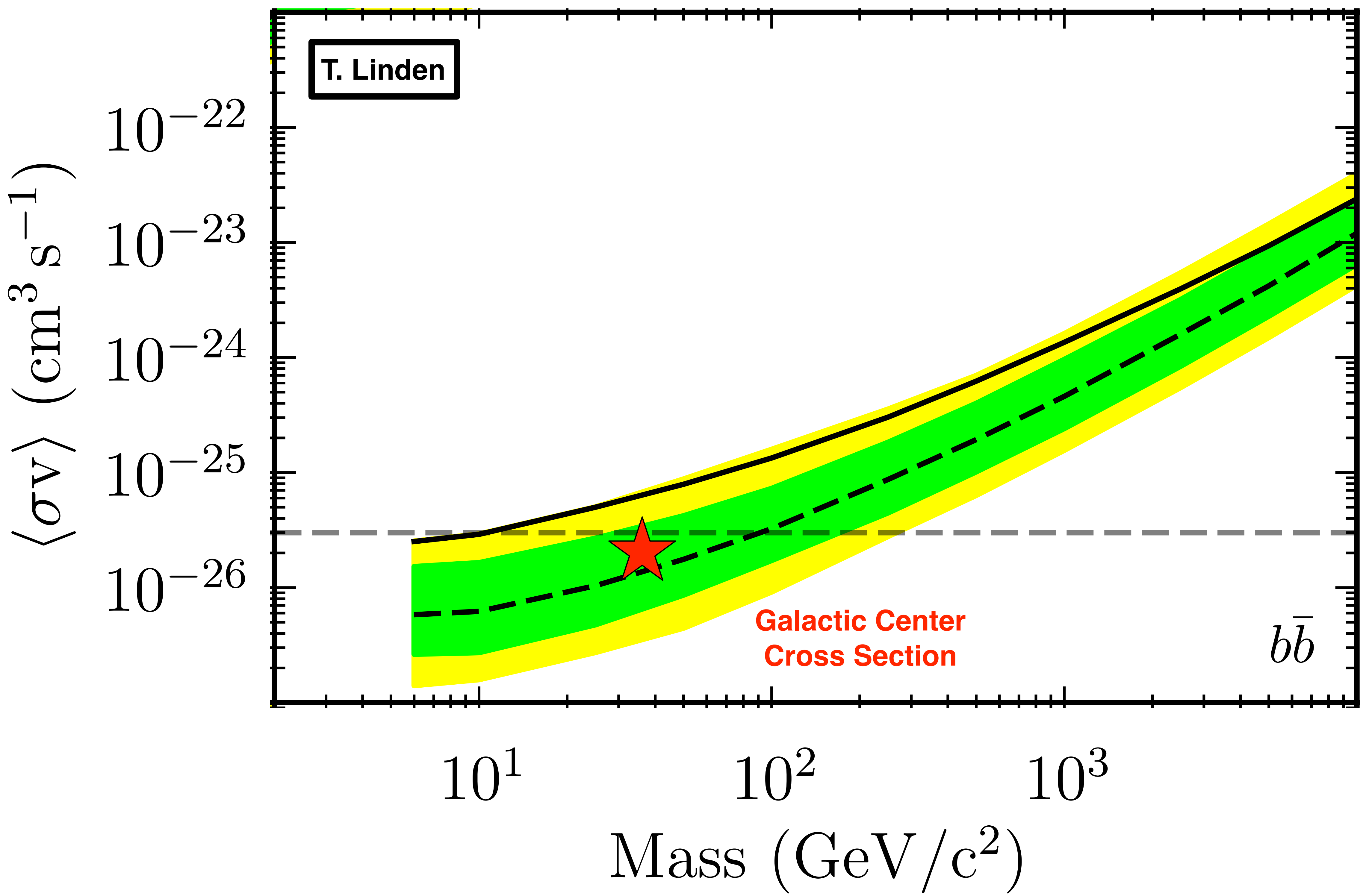
- **Global significance:**
  - **Simulations: p-value = 0.02**
  - **Data: p-value = 0.08**

- **Additional systematic uncertainties:**
  - **Instrument response (< 15%)**
  - **Diffuse backgrounds (< 10%)**
  - **Dark matter profile (< 20%)**



Ackermann et al. PRD 89 042001 (2014)

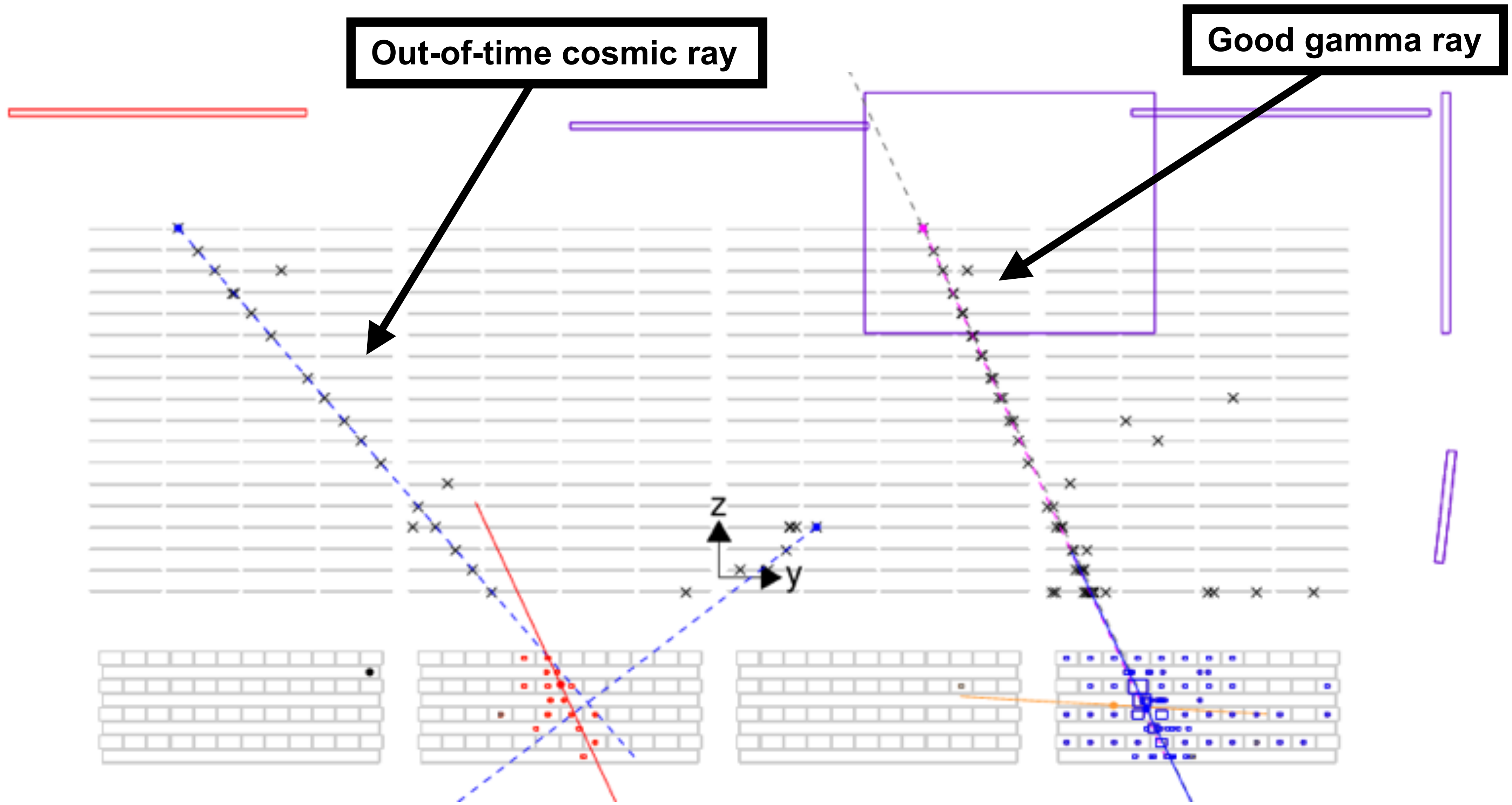
Galactic Center Comparison



Pass 8: Improved LAT Performance

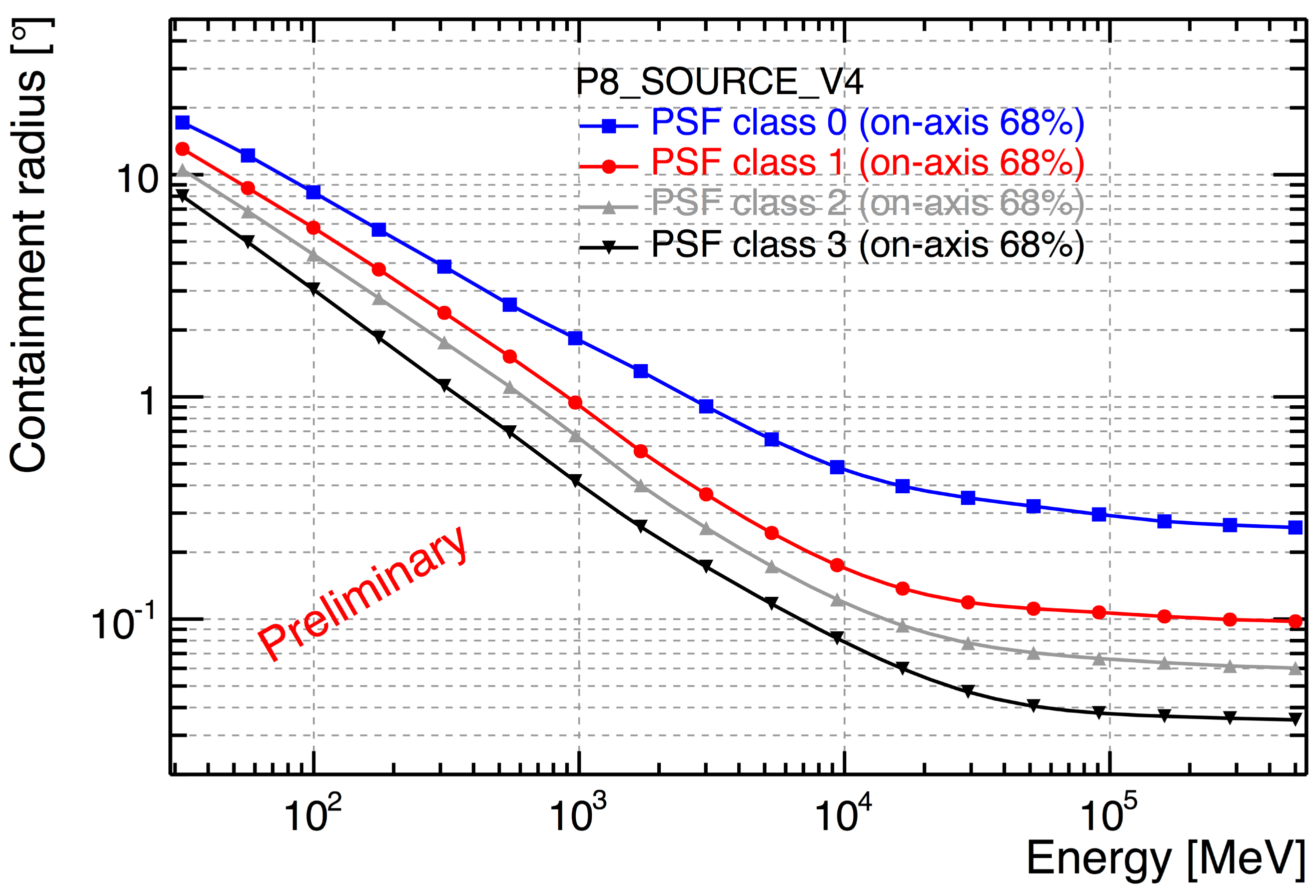
Pass 8: Ghost Busting

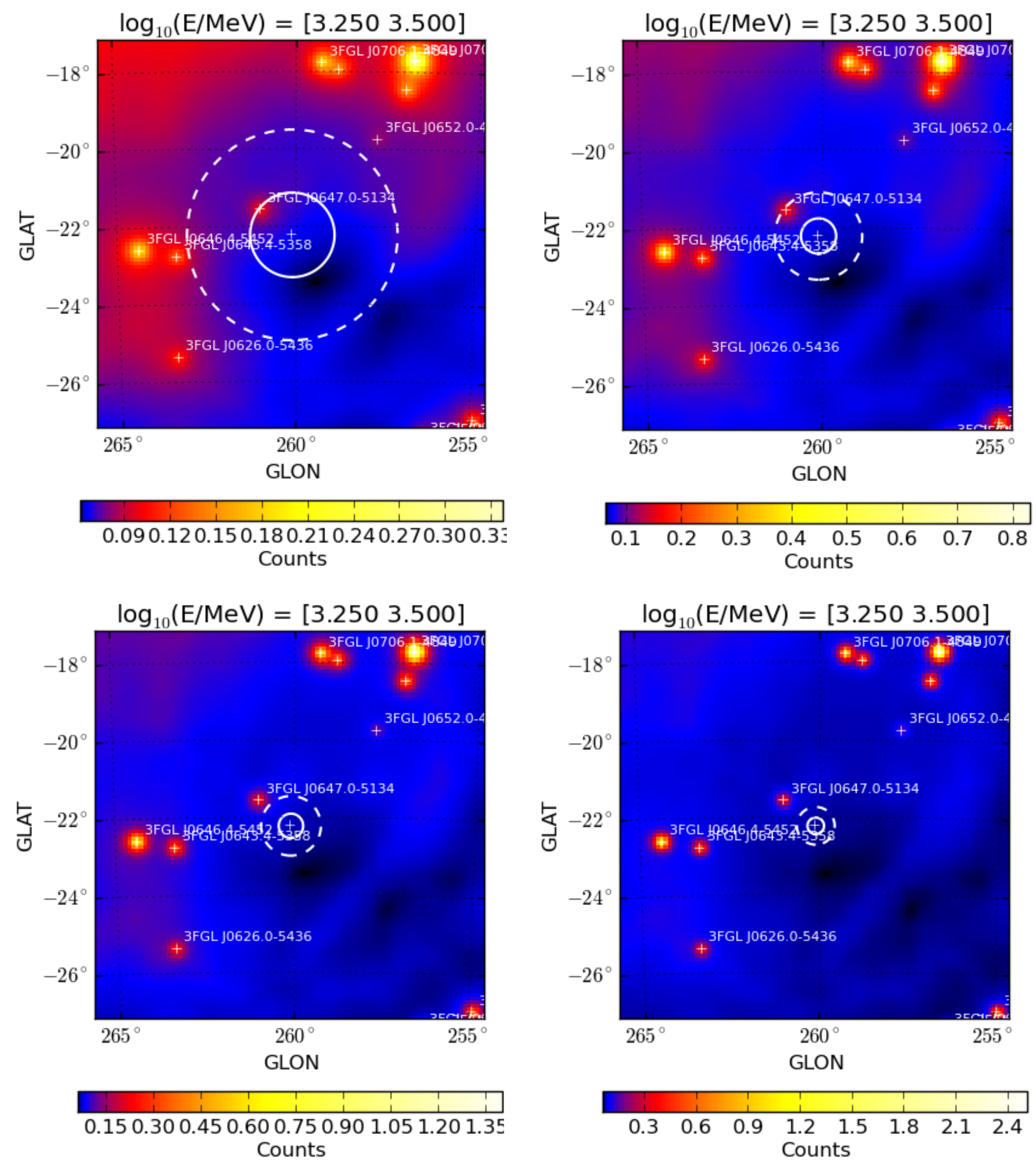
- The Fermi-LAT data is publicly released in packages termed "Passes".
- Each Pass reflects our improved understanding of the instrument and it's environment (detector simulations, event reconstruction, event selection, etc.).
- Pass 8 works from the ground up to remove residual cosmic-ray pile-up.



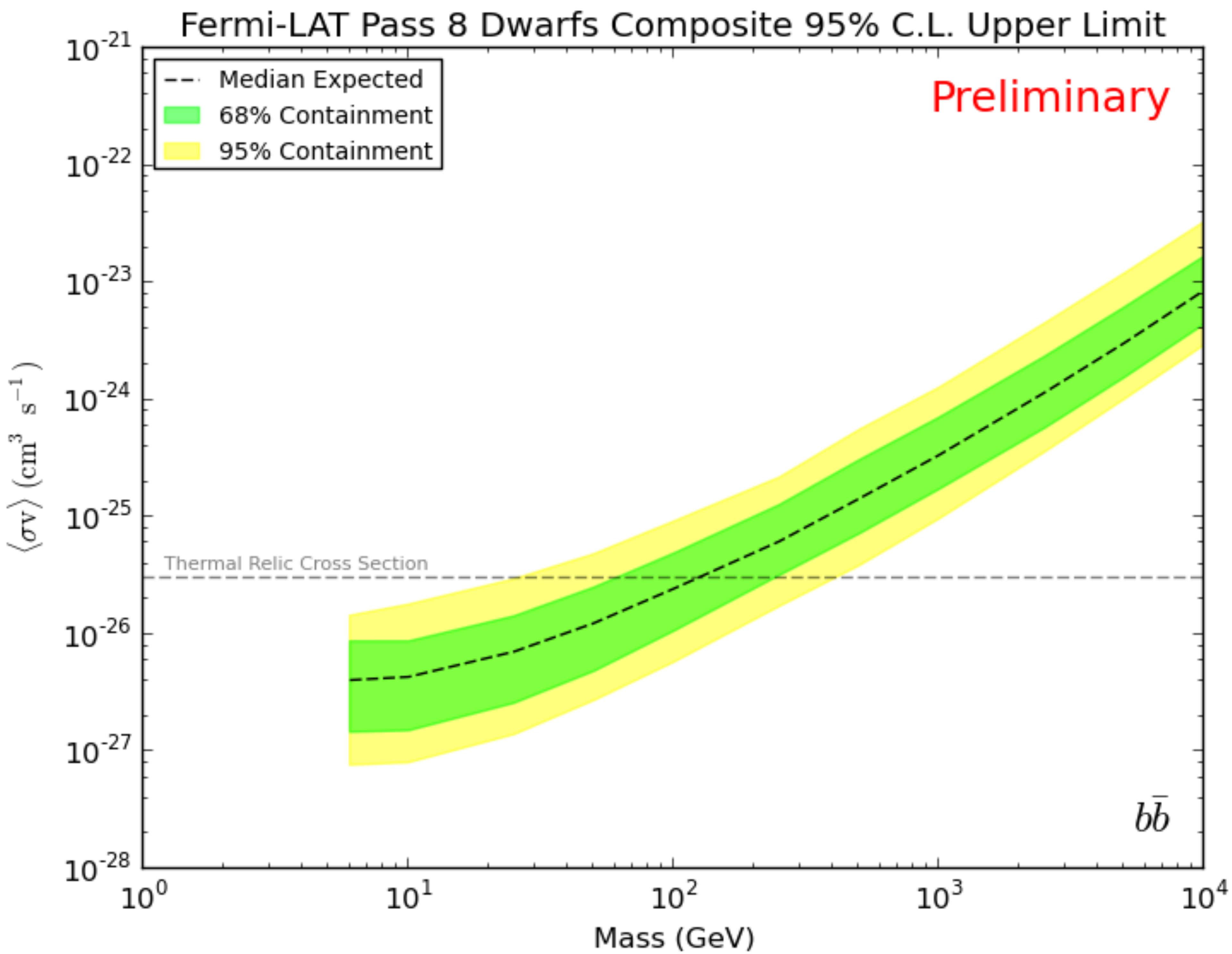
Pass 8: Better "Seeing"

- Events can be divided into classes based on the quality of the event reconstruction.
- Combine events from all PSF event classes into a joint likelihood fit to avoid loss in effective area.
- Results in another ~10-20% gain in point-source sensitivity.

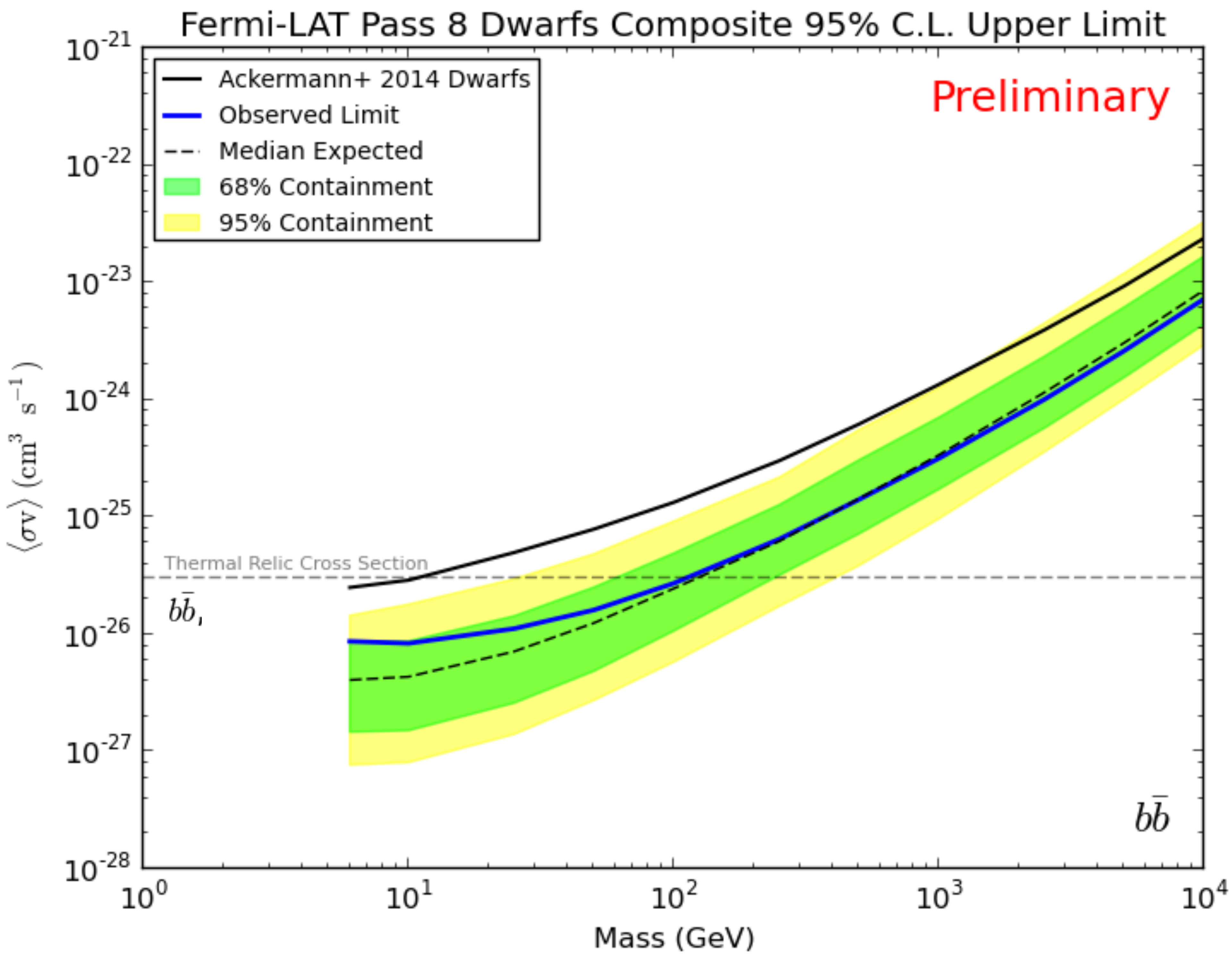




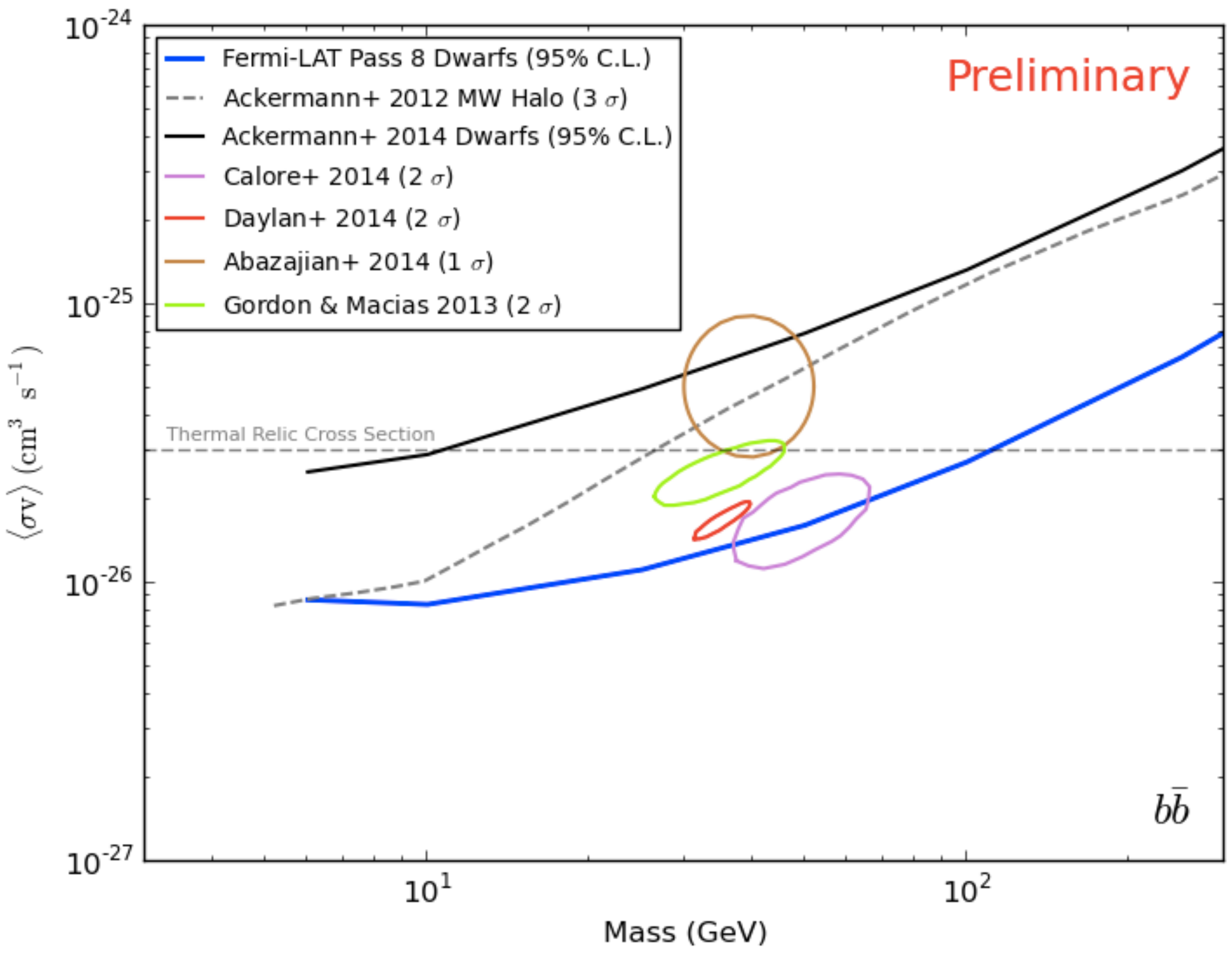
Pass 8 Expected Sensitivity

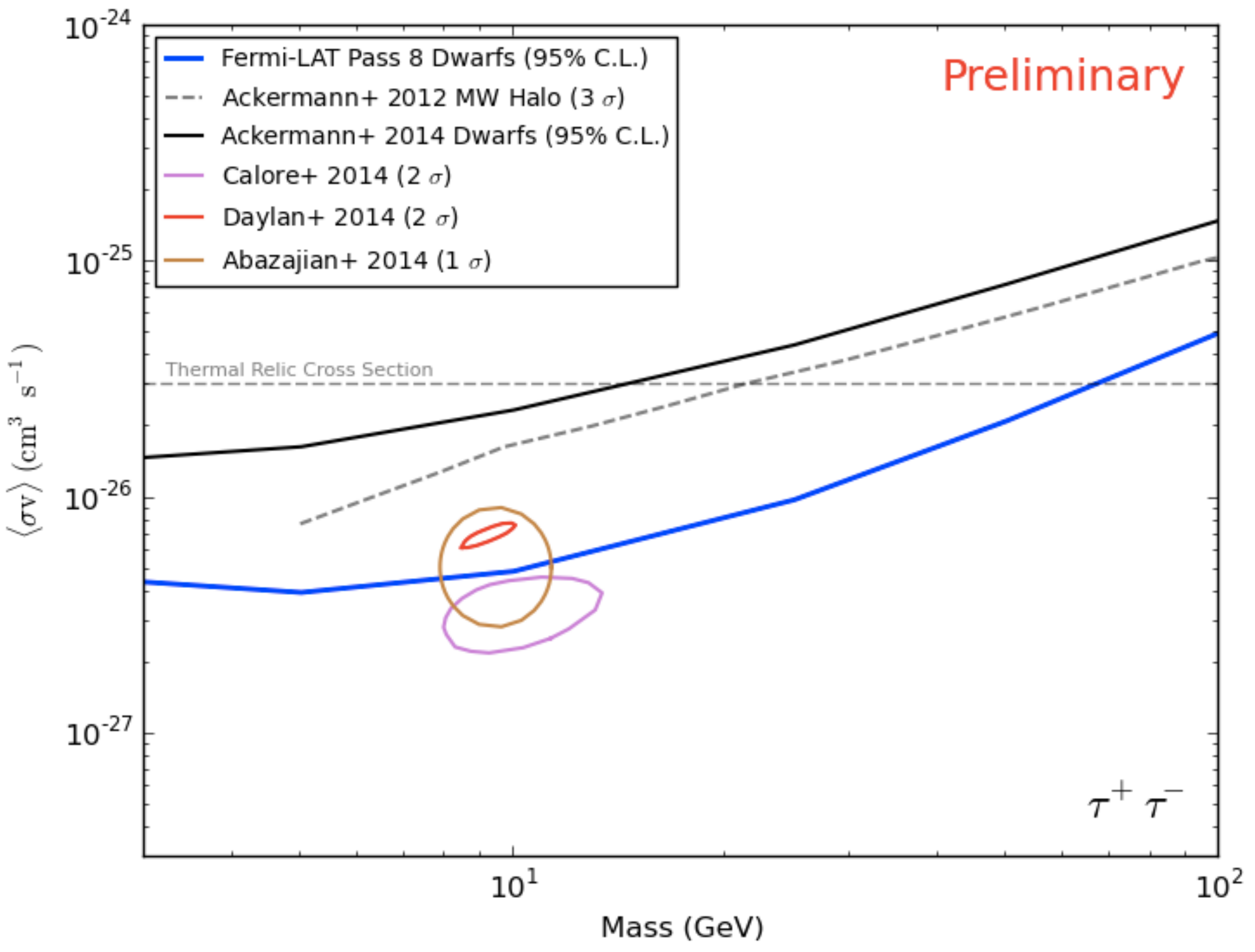


Pass 8 Constraints

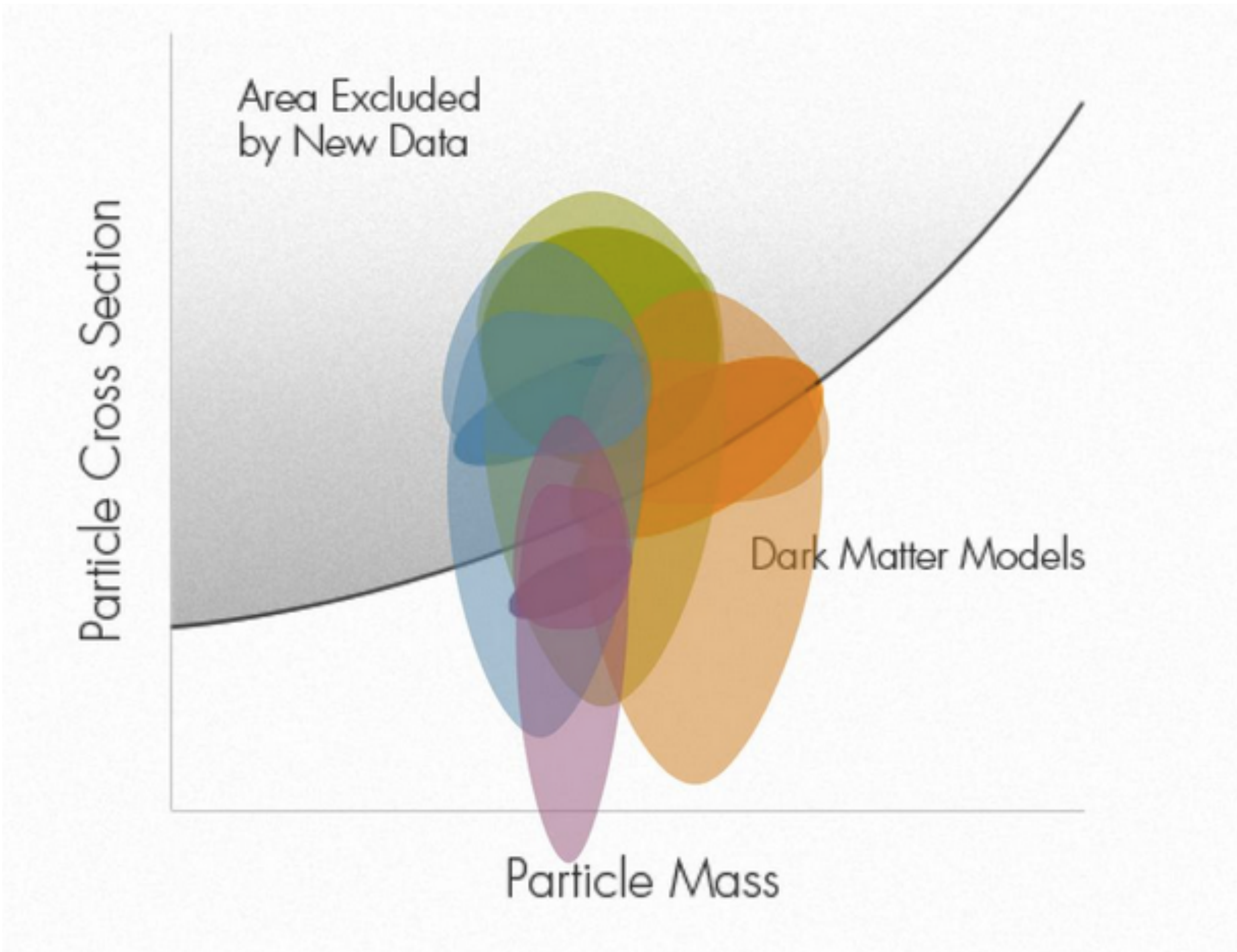


Galactic Center Comparison





Galactic Center Comparison



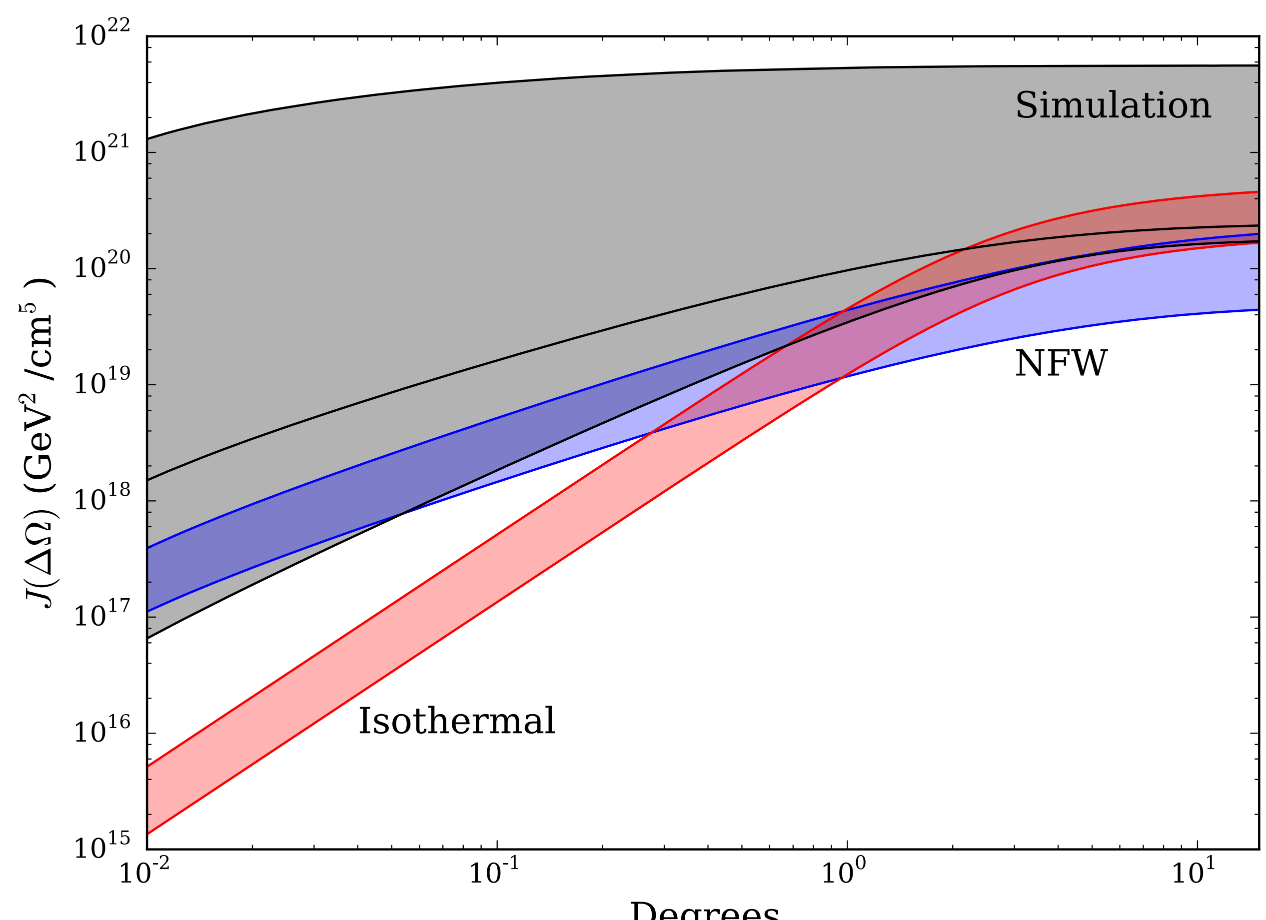
Kevork Abazajian @kevaba · Oct 25
@QuantaMagazine @nattyover I corrected the figure for the article to reflect the approx. halo density uncert to 2σ

1

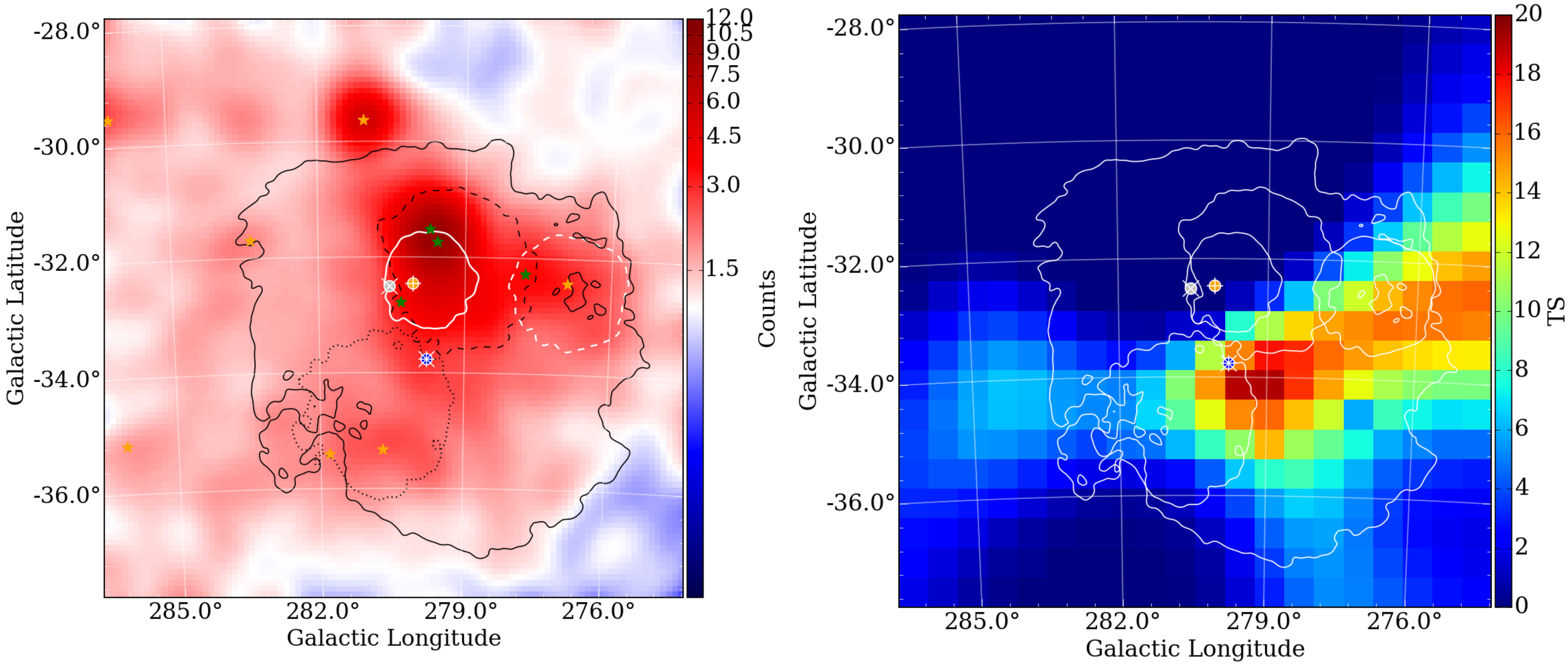
Other Targets

Other Targets: The LMC

- The Large Magellanic Cloud (LMC) is the largest Milky Way satellite galaxy.
- Expected to be the second brightest dark matter signal region (after the Galactic Center)
- Dwarf irregular galaxy
  - Active star formation
  - Cosmic-ray acceleration
  - Plentiful gas and dust
- The LMC is a strong, spatially extended gamma-ray source
- Control for systematic by using regions around the LMC as a "side-band"

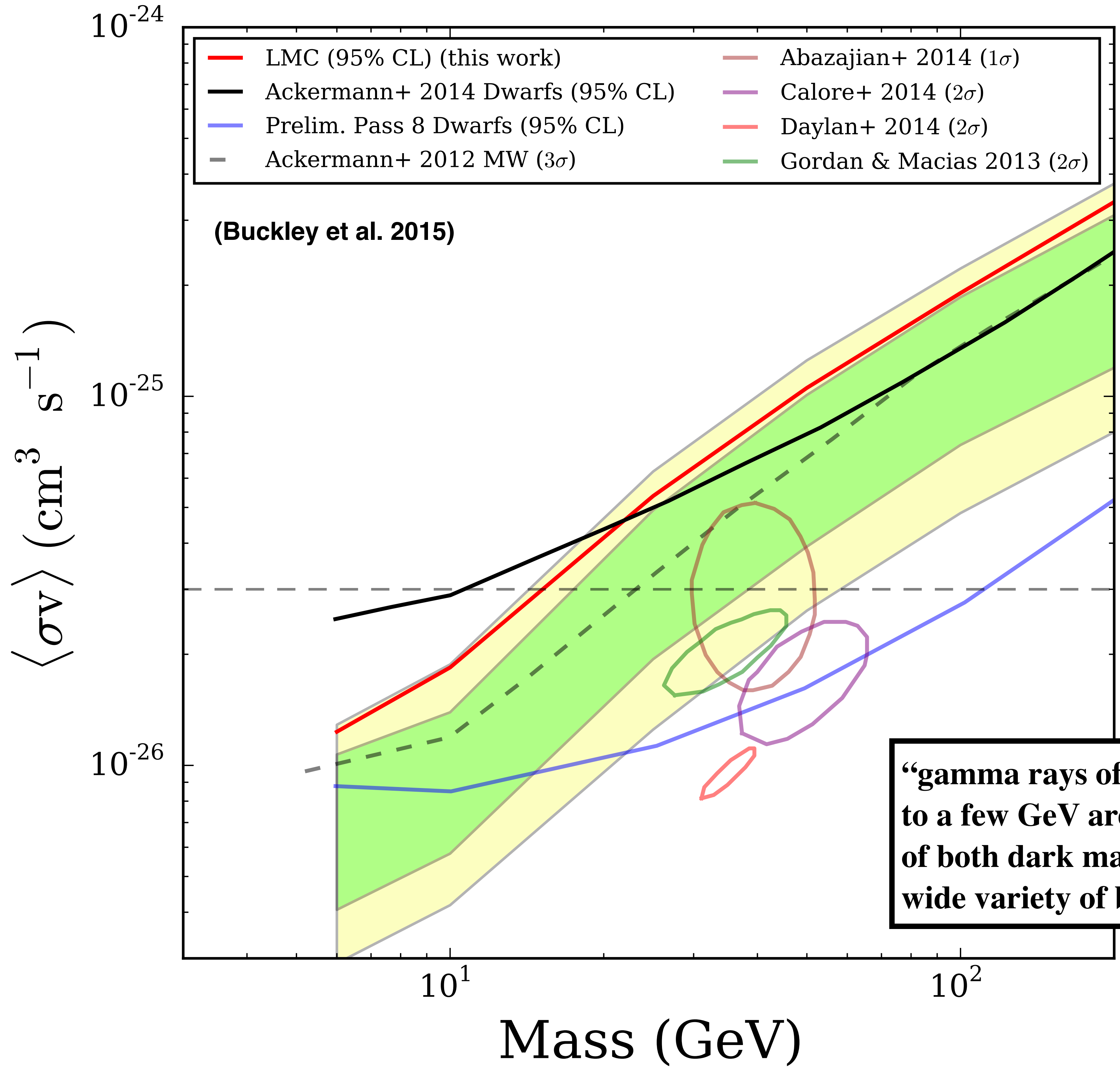


Other Targets: The LMC



(Buckley et al. 2015)

Other Targets: The LMC



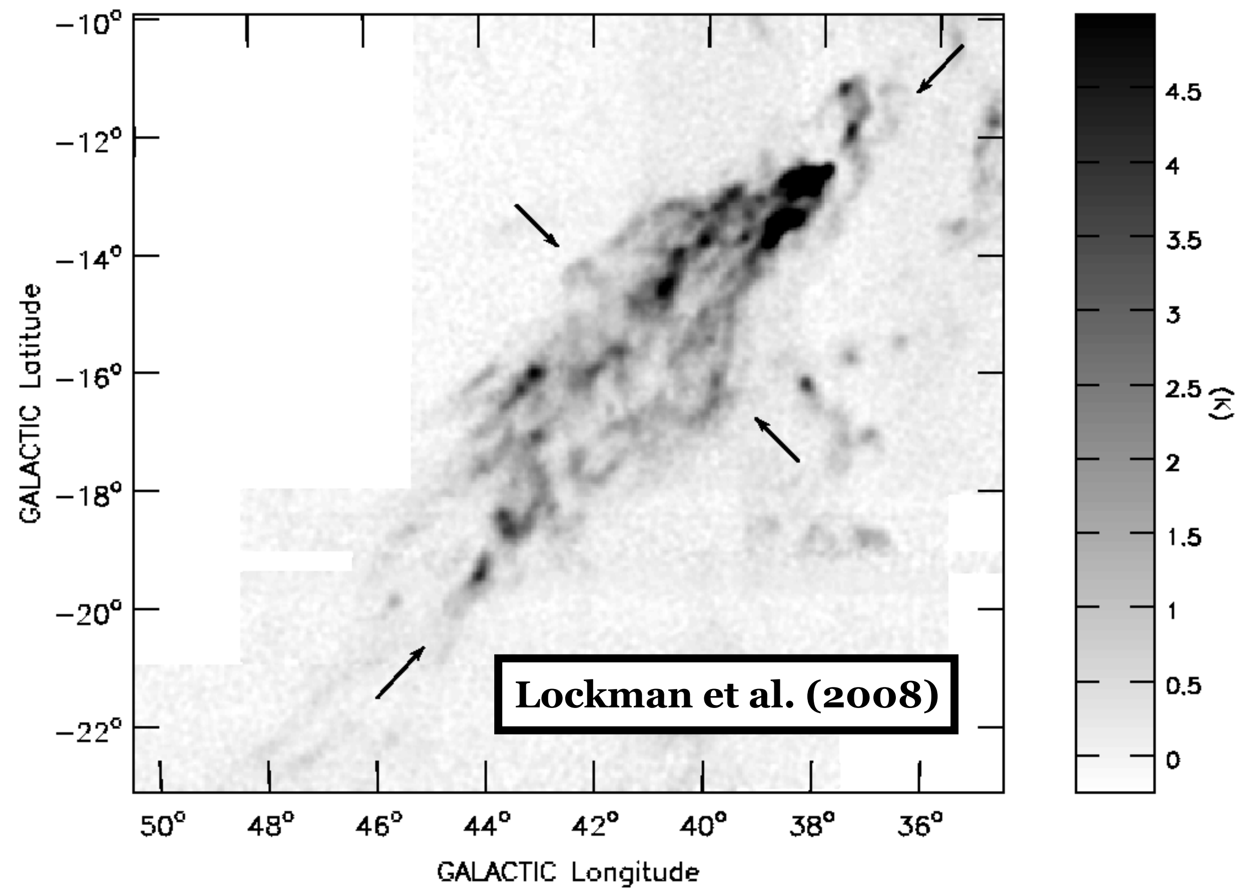
"gamma rays of a few hundred MeV to a few GeV are the generic expectation of both dark matter annihilation and a wide variety of baryonic backgrounds"

Other Targets: The Smith Cloud

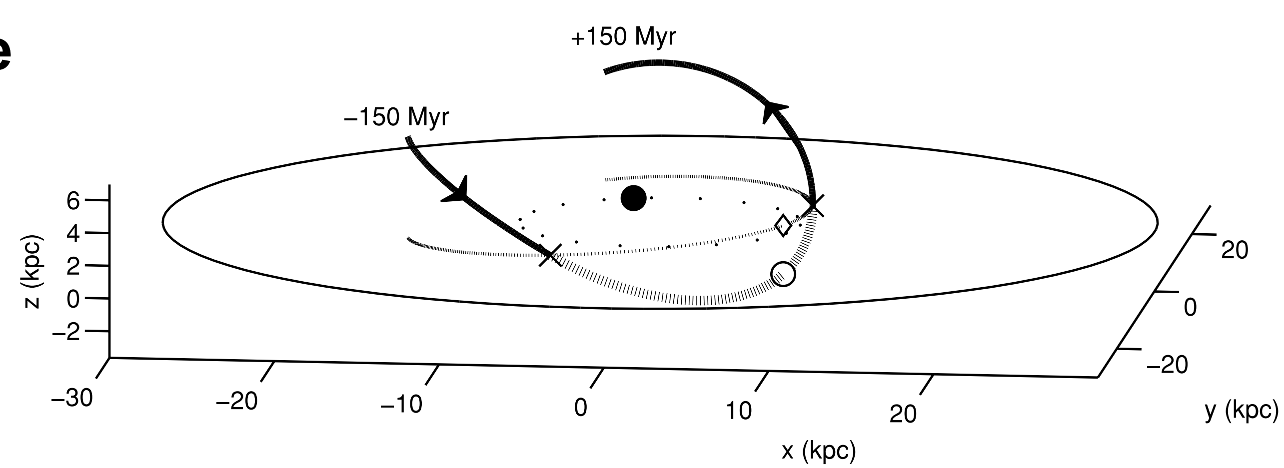
- The **Smith Cloud** is one of the best characterized HVCs (e.g., Lockman et al. 2008)

- The Smith Cloud resides at a heliocentric distance of **12.4 +/- 1.3 kpc** (nearest dwarf galaxy at 23 kpc).

- The 3D trajectory of the Smith Cloud suggests that it **passed through the Galactic disk** ~70 Myr ago.

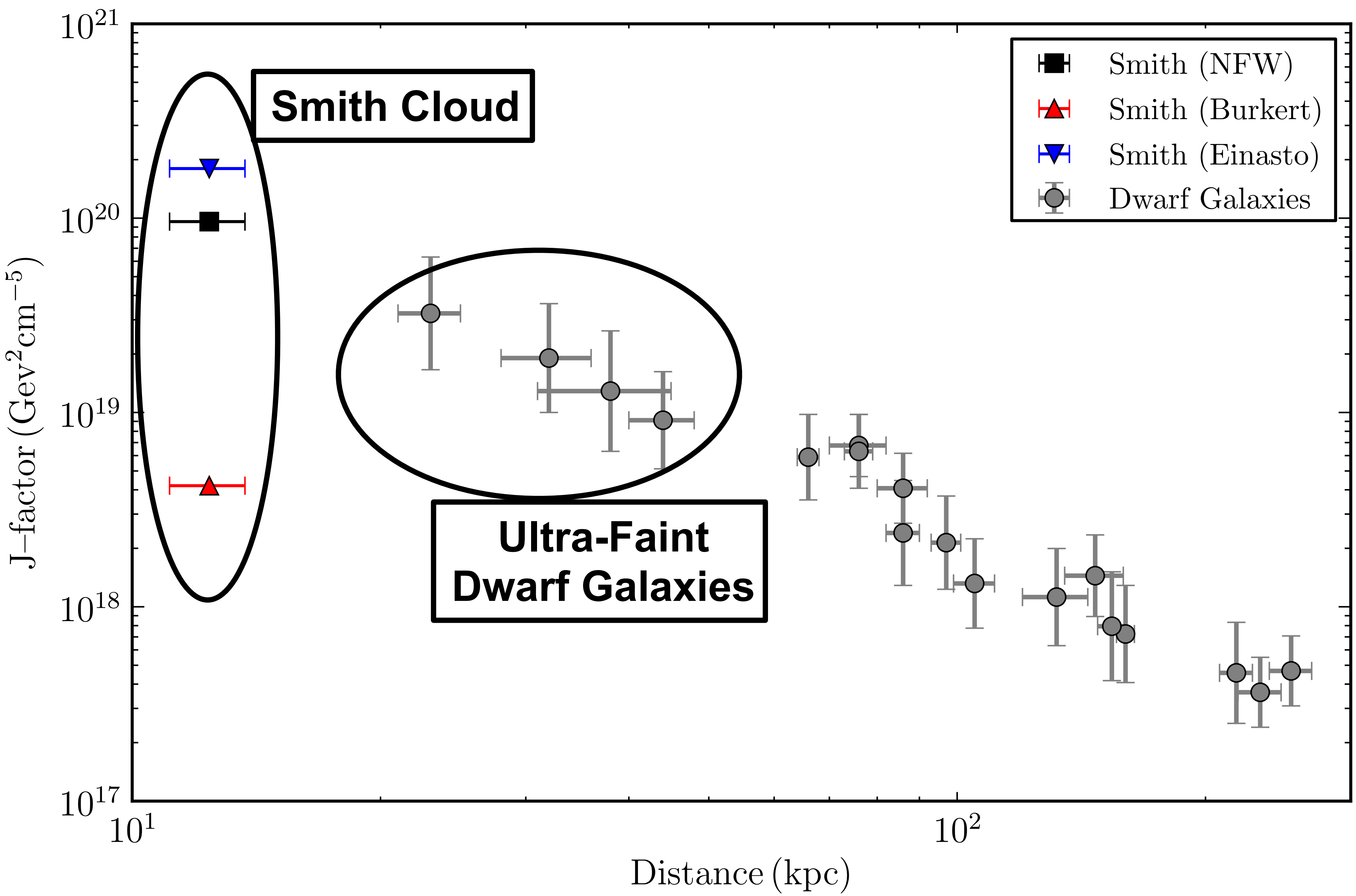


- The gaseous component of the cloud has a weak self-gravity and ram pressure forces would **dissipate the cloud** during a passage through the Galactic disk.

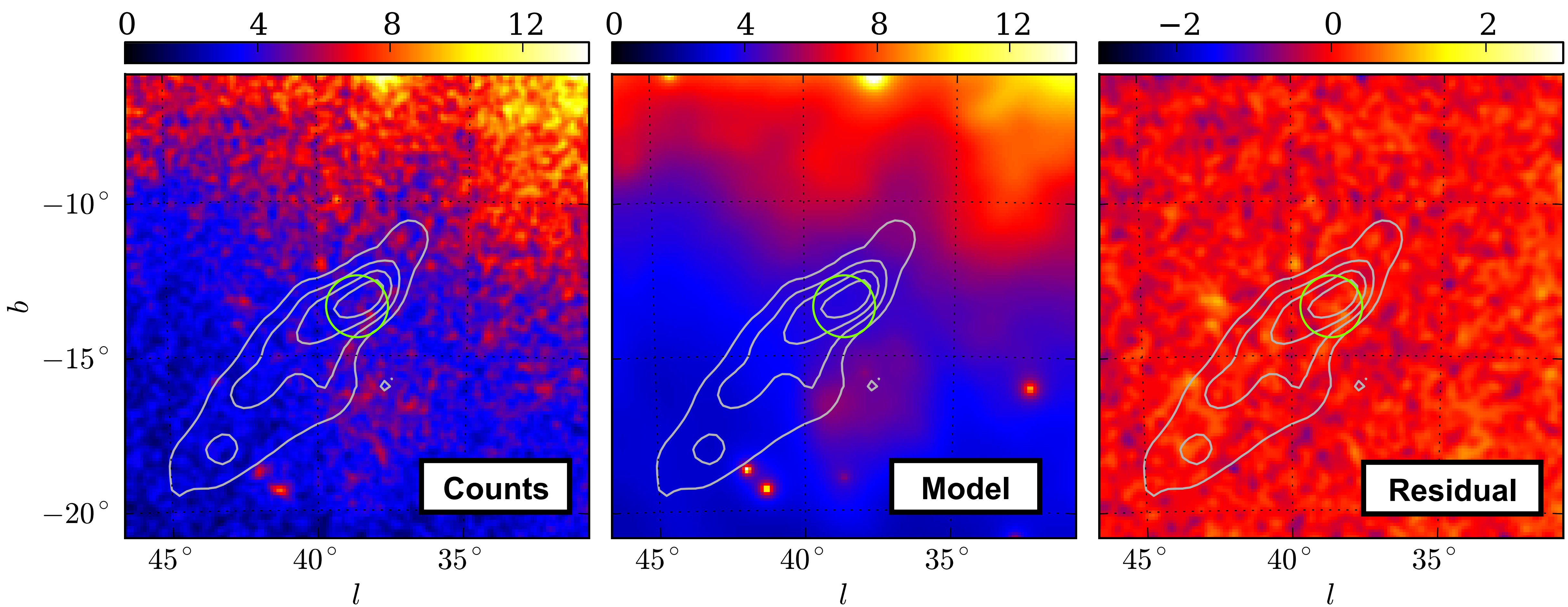


- This suggests that the Smith Cloud may be bound by a **dark matter halo** with tidal mass ~10^8 $M_\odot$ (Nichols & Bland-Hawthorn, 2009).

Other Targets: The Smith Cloud

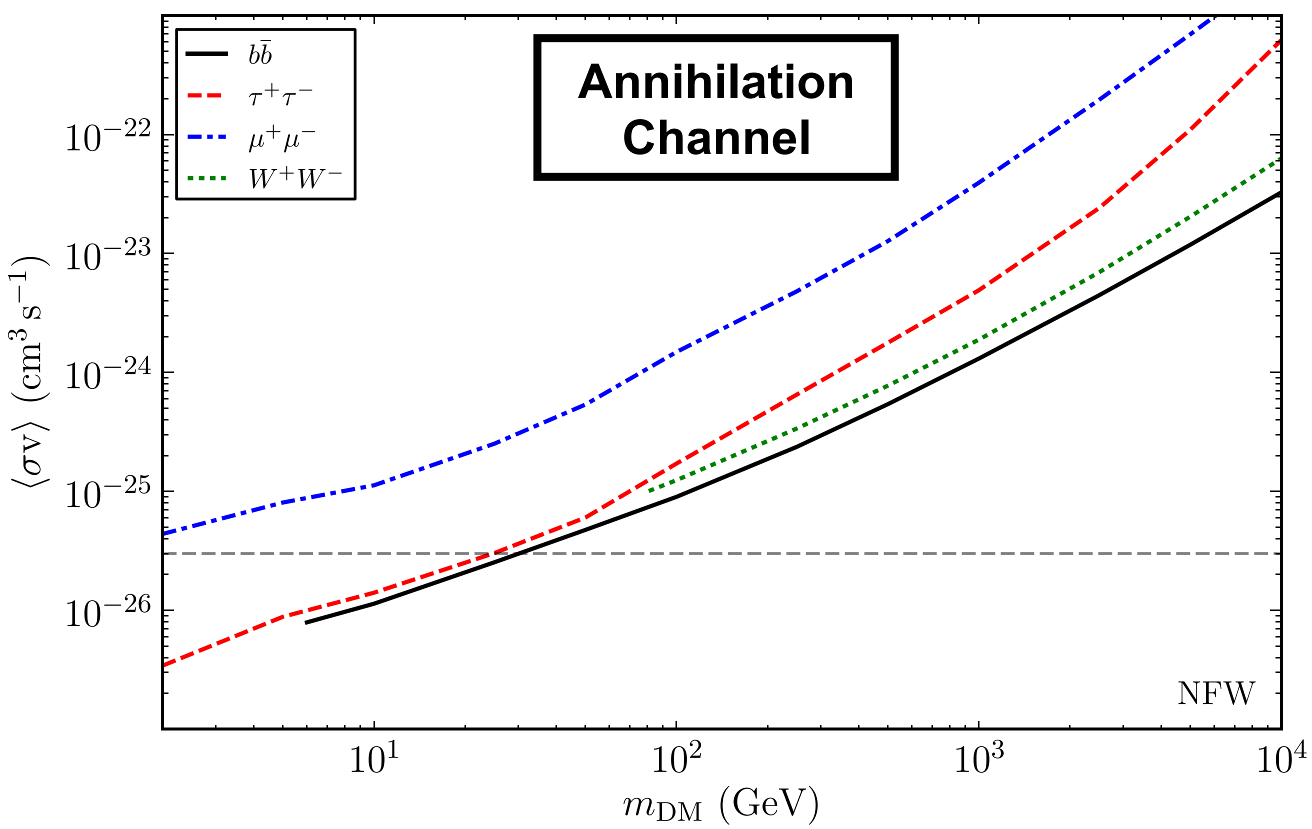


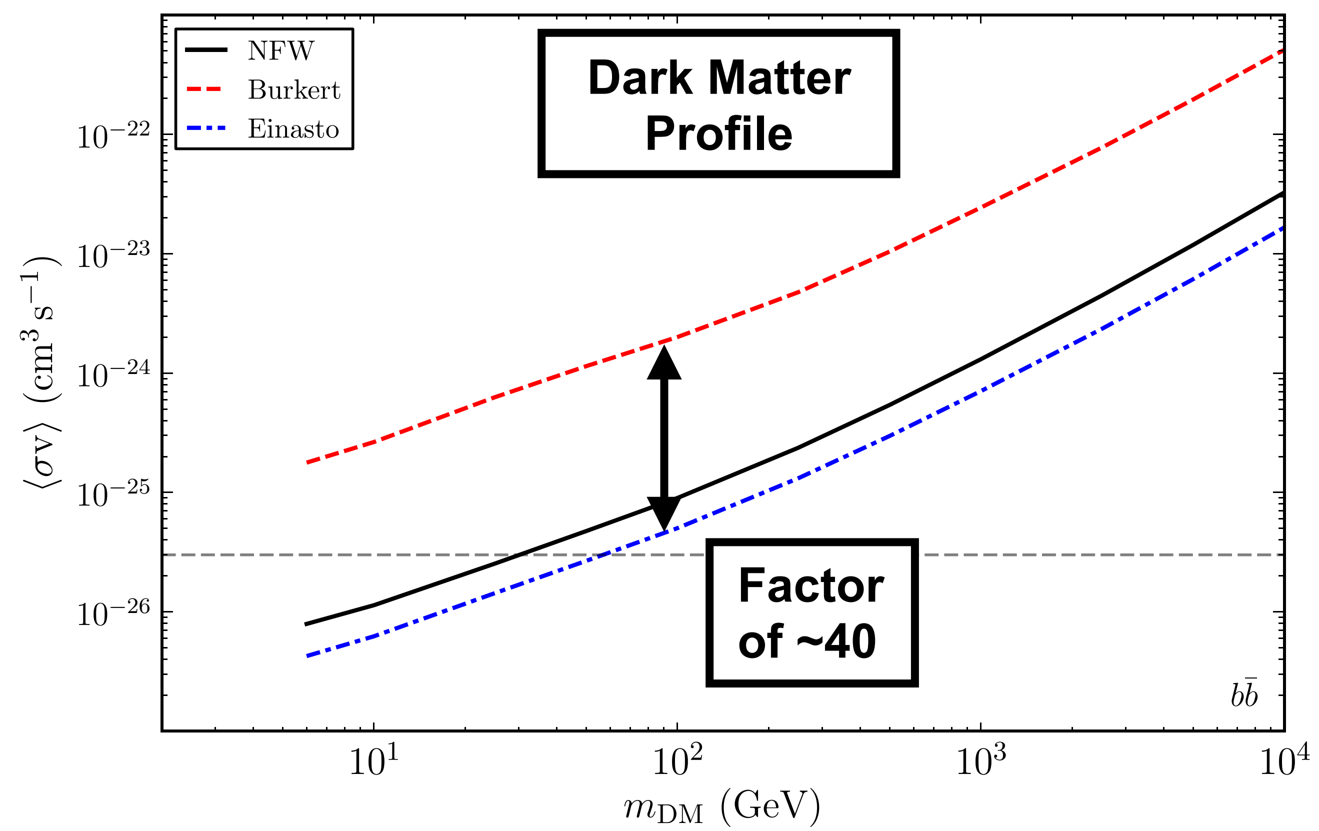
Other Targets: The Smith Cloud



- **5-year binned likelihood analysis from 500 MeV to 500 GeV over a 15˚x15˚ ROI surrounding the Smith Cloud (P7REP_CLEAN_V15).**
- **Likelihood model includes 2FGL sources, the custom diffuse Galactic foregrounds, and a local isotropic component modeled with a broken power-law.**
- **Set bin-by-bin limits on the gamma-ray flux from the Smith Cloud using a spatially-extended model of the dark matter annihilation signal.**
- **No significant excess found for any of the spatial or spectral models tested (maximum TS = 4.7)**

Other Targets: The Smith Cloud

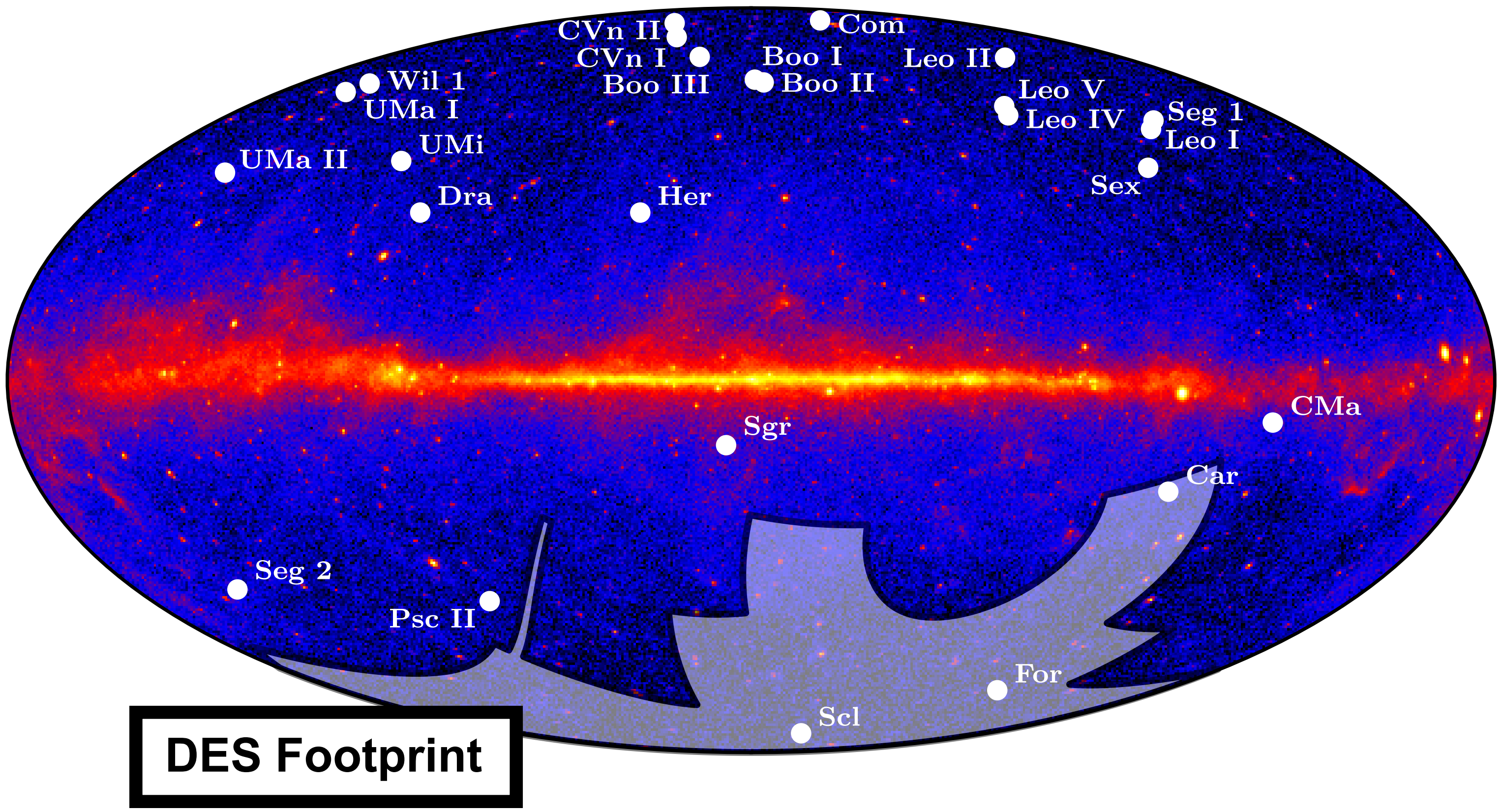


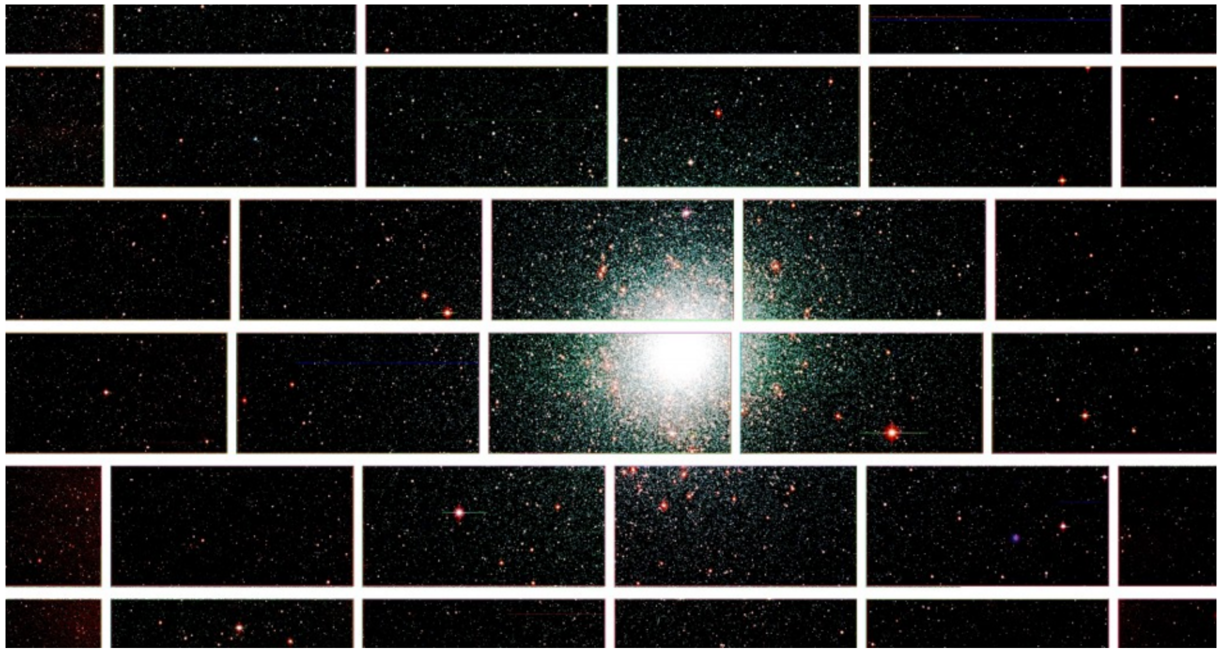


Why Fermilab?

Other Targets: New Dwarf Galaxies

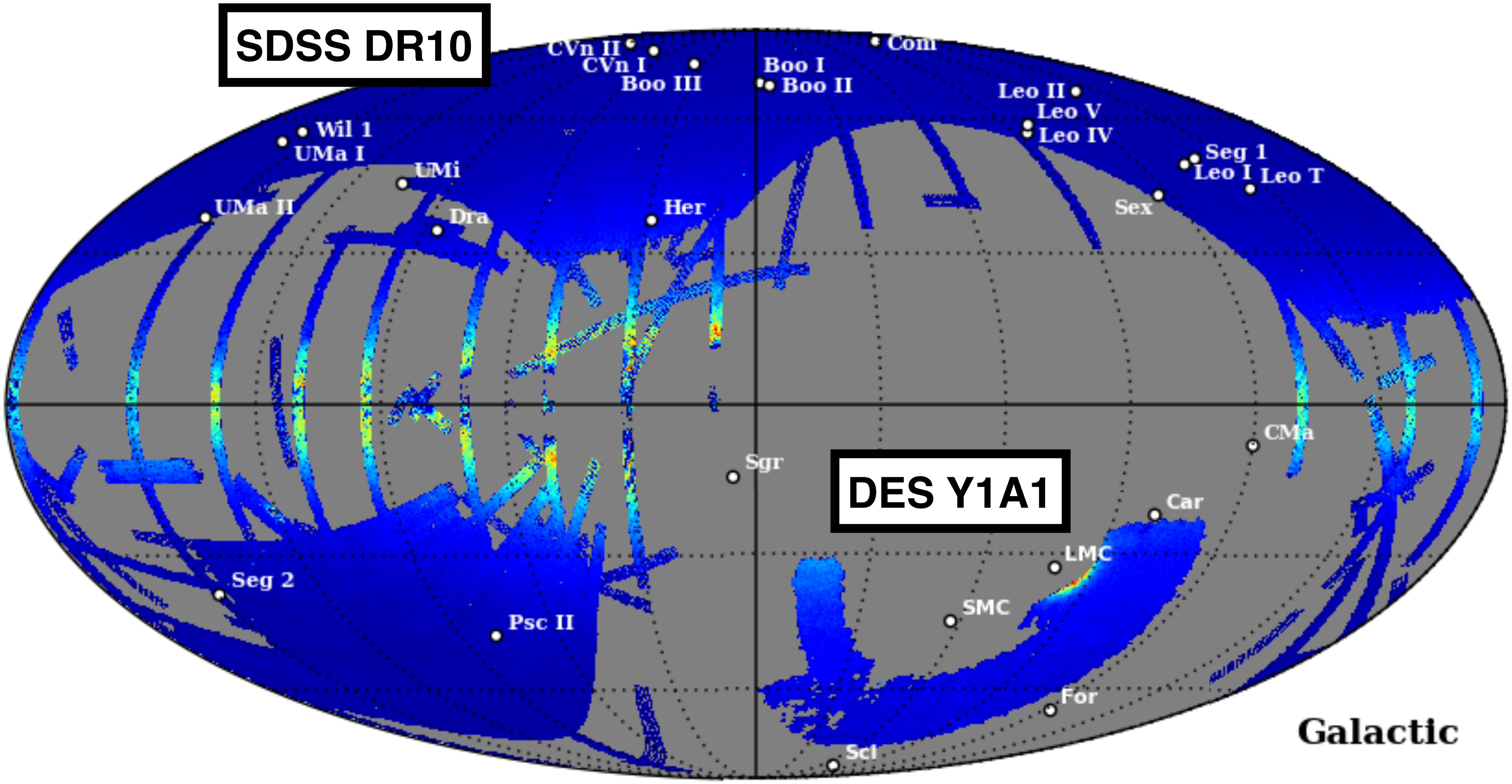
- **The number of known dwarfs doubled due to SDSS.**
  – SDSS only covers ~25% of the sky
  – SDSS has a magnitude limit of ~22
- **New wide-field surveys plan to greatly expand our coverage:**
  – Pan-STARRS:
    ~75% of the sky from the north
  – Southern Sky Survey:
    ~75% of the sky from the south
  – DES:
    ~5000 deg^2 in the south (deeper)
  – LSST:
    ~50% of the sky (much deeper)
- **Eventually hope to be complete for all bound satellite galaxies ($L > 10^2\ L_\odot$)**
- **Simulations predict hundreds of Milky Way satellite galaxies may be found (Tollerud et al., 2008; Hargis et al., 2014)**





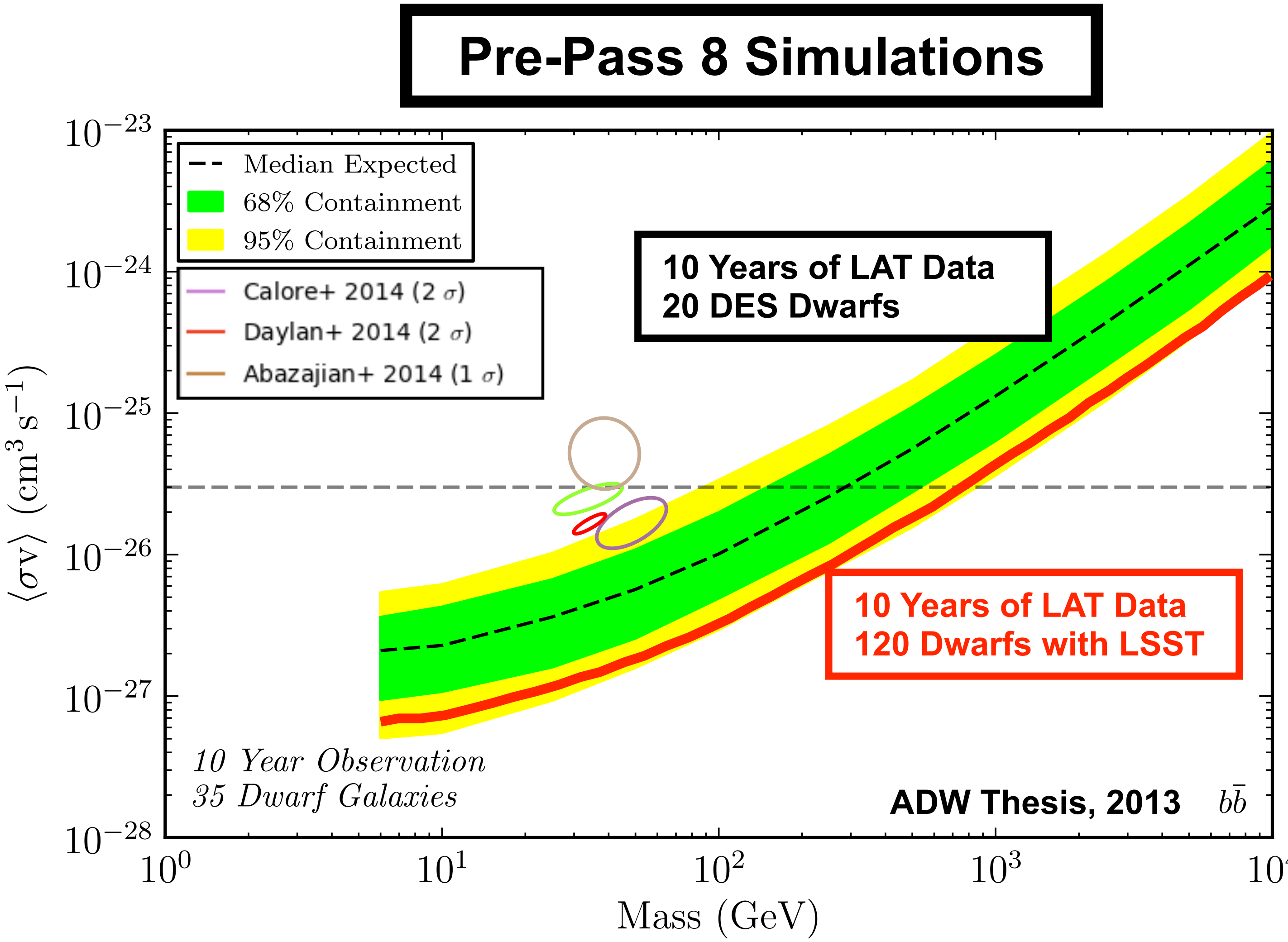
Globular Cluster 47 Tuc (DES Collaboration)

Other Targets: New Dwarf Galaxies



Other Targets: New Dwarf Galaxies

- Project that DES will find 20 additional dwarf galaxies.
- Assume that the characteristics of these new galaxies are similar to those recently discovered by SDSS.
  - High Galactic latitude
  - Comparable J-factors and uncertainties
- Combine additional dwarfs with continued LAT operations.
  - 10 years of LAT data taking
  - Current instrument performance
- Expect sensitivity to the thermal relic cross section for dark matter particles with masses ~350 GeV
- LSST may find > 100 dwarf galaxies



Summary

Summary

- **Indirect detection is a powerful and complementary technique in the search for dark matter.**
- **The Fermi-LAT has unprecedented sensitivity in this field and is operating exceptionally well (Pass 8 public data release scheduled for the end of March).**
- **The Galactic Center has the largest expected dark matter signal, but is a complex region dominated by systematic uncertainties.**
- **The Galactic Center excess emission is intriguing, but requires confirmation in cleaner target regions.**
- **Milky Way dwarf satellite galaxies are pristine laboratories for dark matter searches.**
- **The discovery of new dwarf galaxies will increase the sensitivity of indirect dark matter searches**

Backup Slides

Back-up Slides: General

Gamma-ray Source Identification

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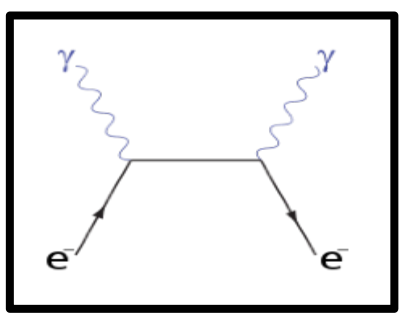

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<u>Energy Source</u>
Explosion
Rotation
Accretion

<u>Accelerator</u>
Shocks
Magnetic reconnection
etc.

<u>Target Material</u>
Gas & Dust
Photon Fields
etc.

<u>Gamma-rays</u>

The gamma-ray sky is a crowded and exciting place

Non-thermal emission often leaves tracers at other wavelengths

Correlated Variability: Coincident flux variations across wavelengths

Timing: Periodicity of pulsars

Spatial Morphology: Spatially extended sources

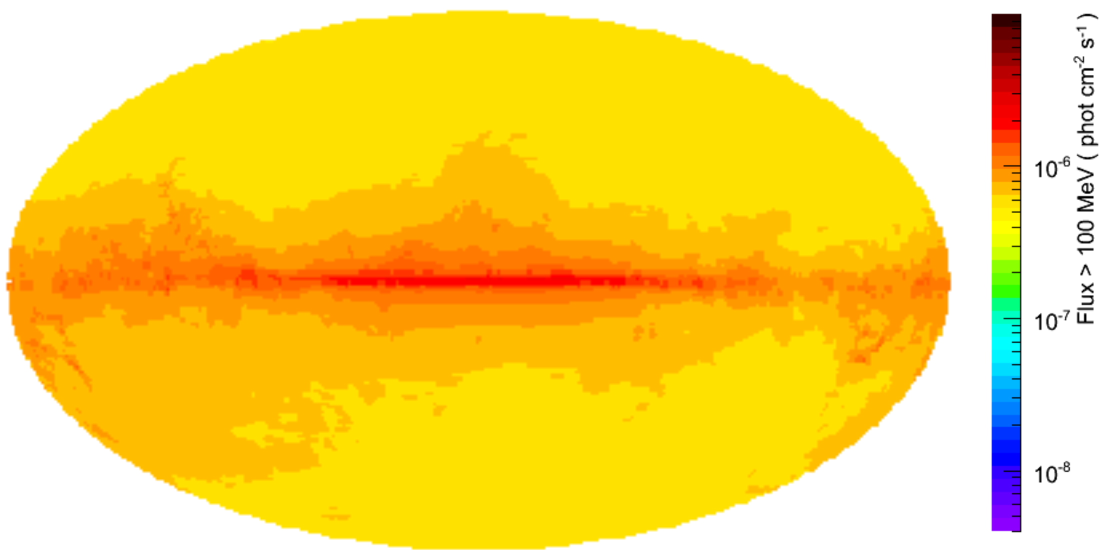
Spatial Coincidence: Source localization

Spectral continuity: Look at bounding energy regimes

Combination of data across multiple instruments is essential

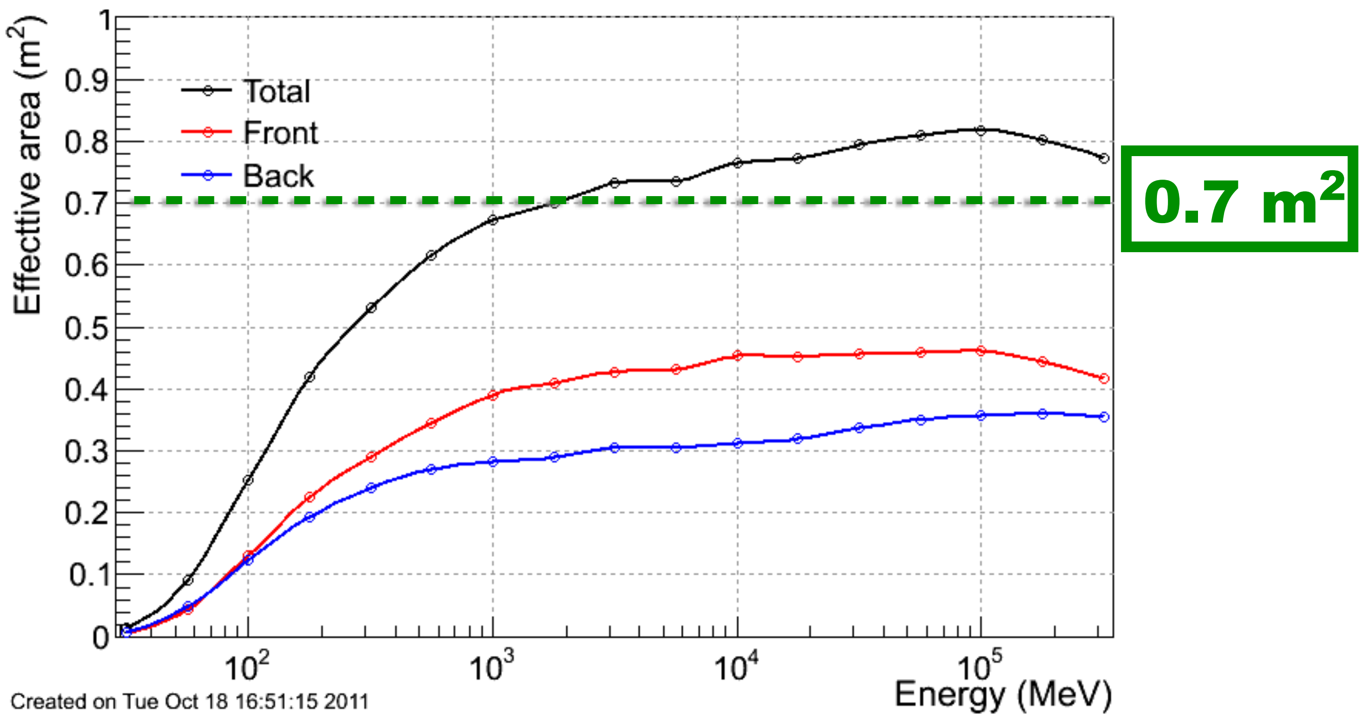
Fermi-LAT Performance

All-Sky Coverage

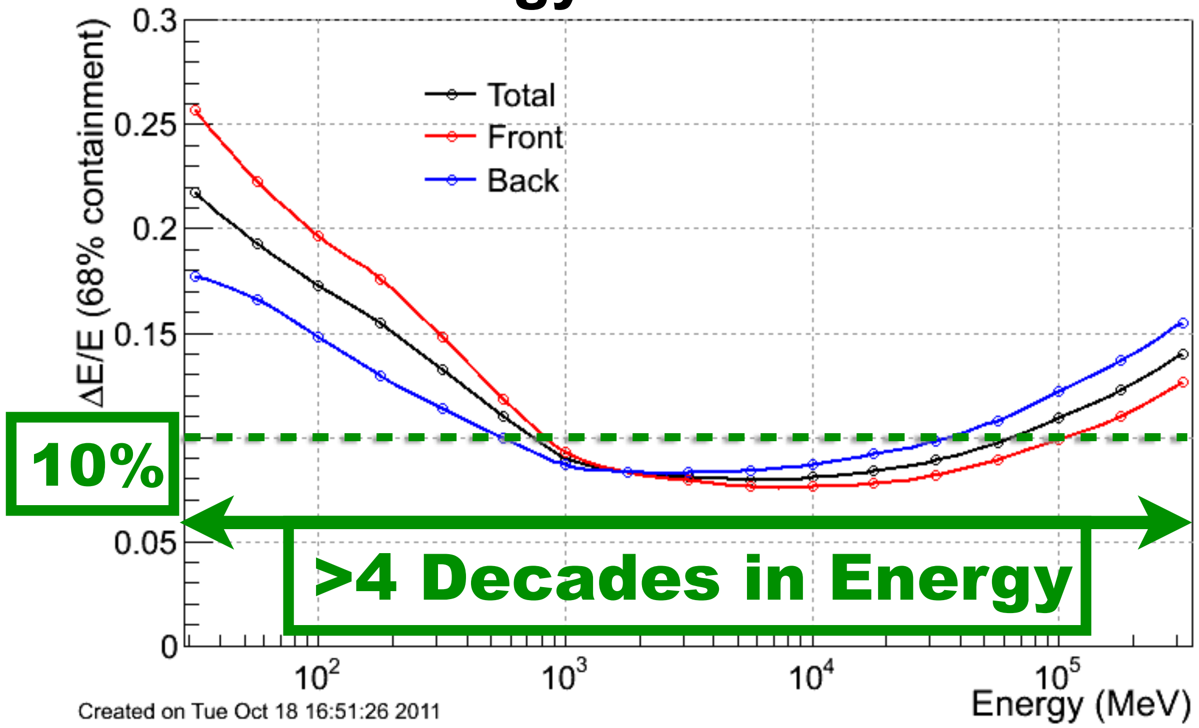


Every ~3 Hours

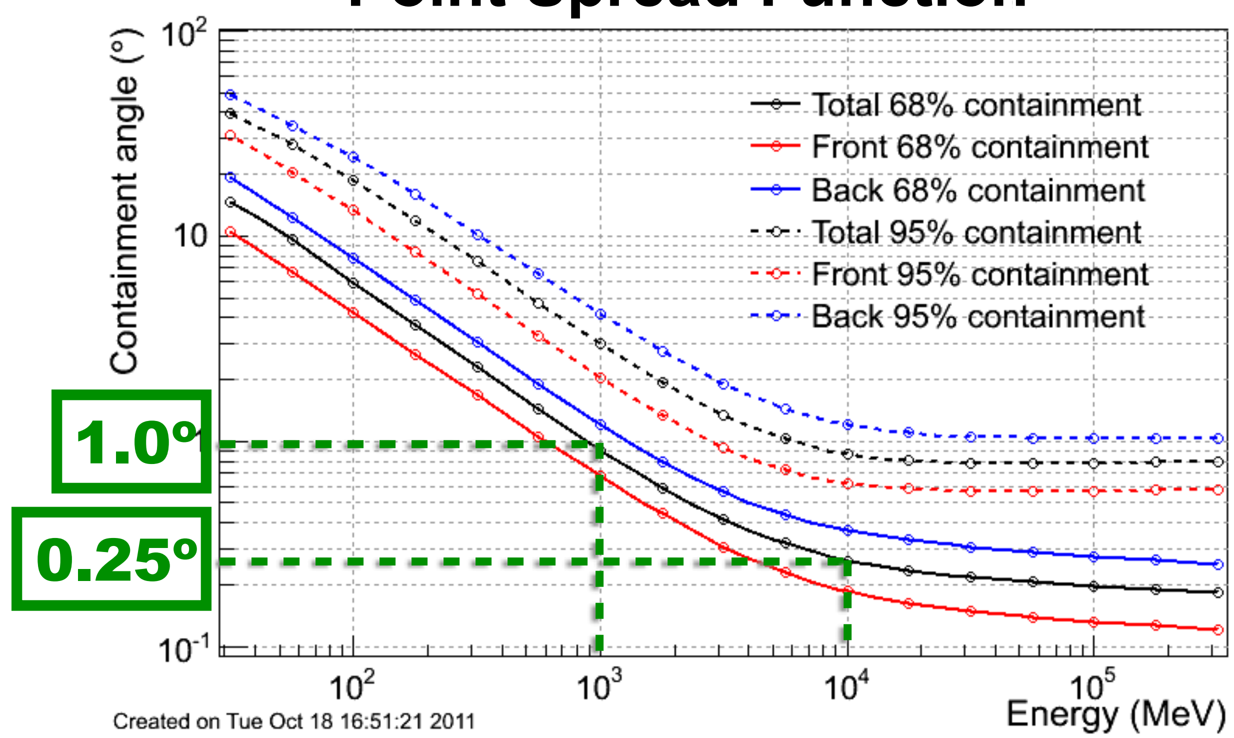
Effective Area



Energy Resolution



Point Spread Function

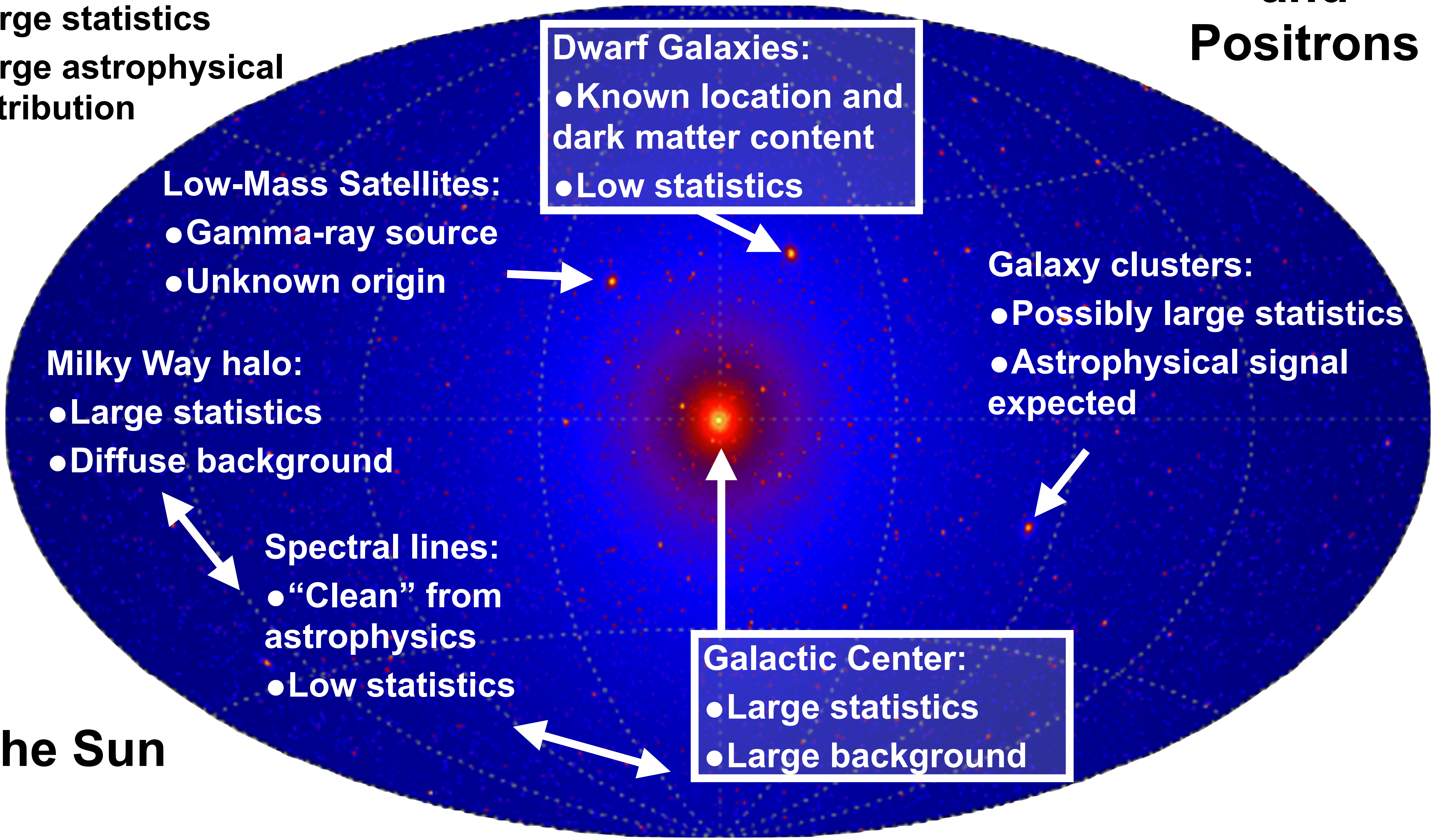


Dark Matter Distribution

$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

Extragalactic background:
- Large statistics
- Large astrophysical contribution

Electrons and Positrons



The Sun

Piere et al. Phys Rev D83, 023581 (2011)

Dark Matter Distribution

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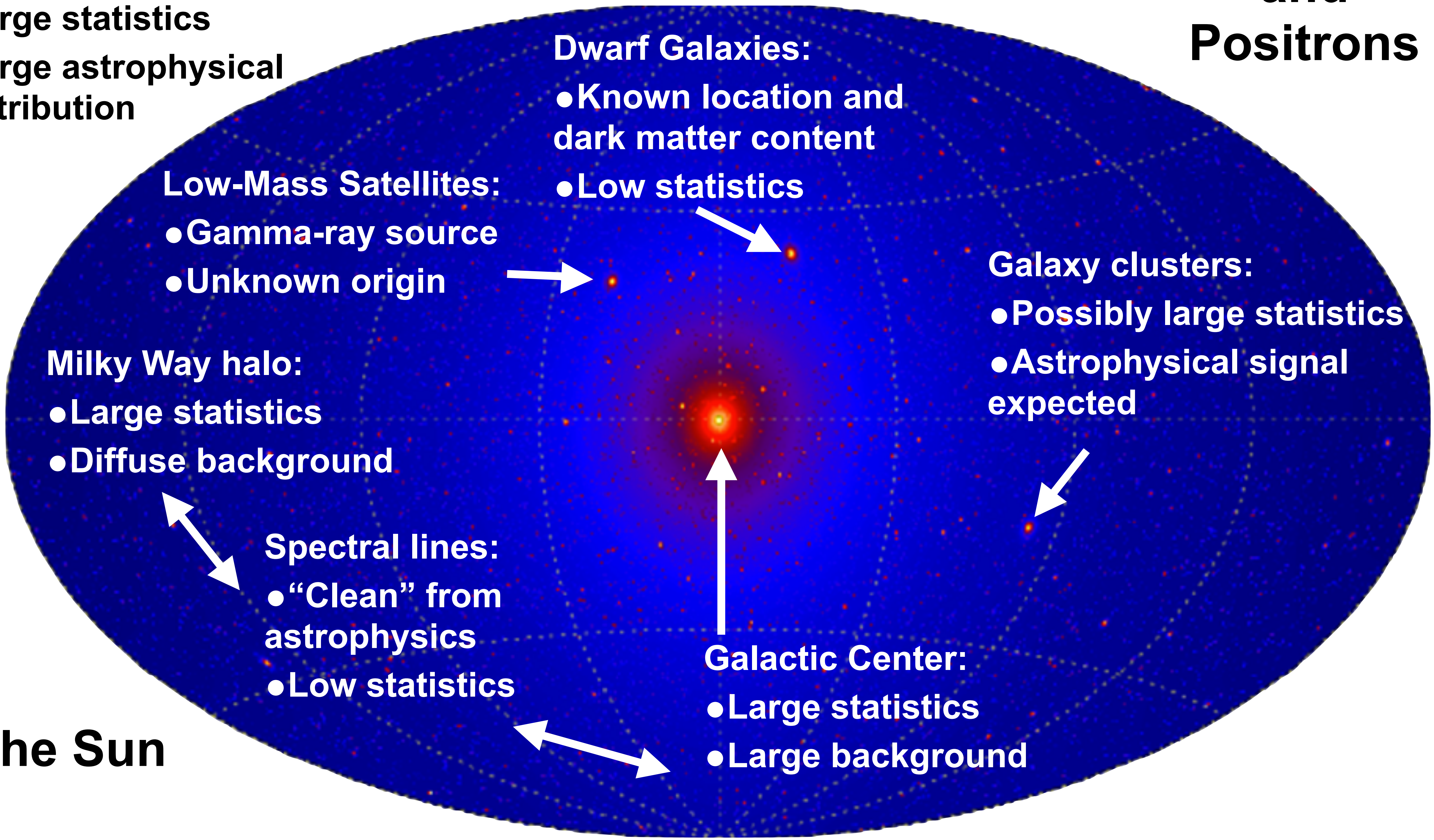
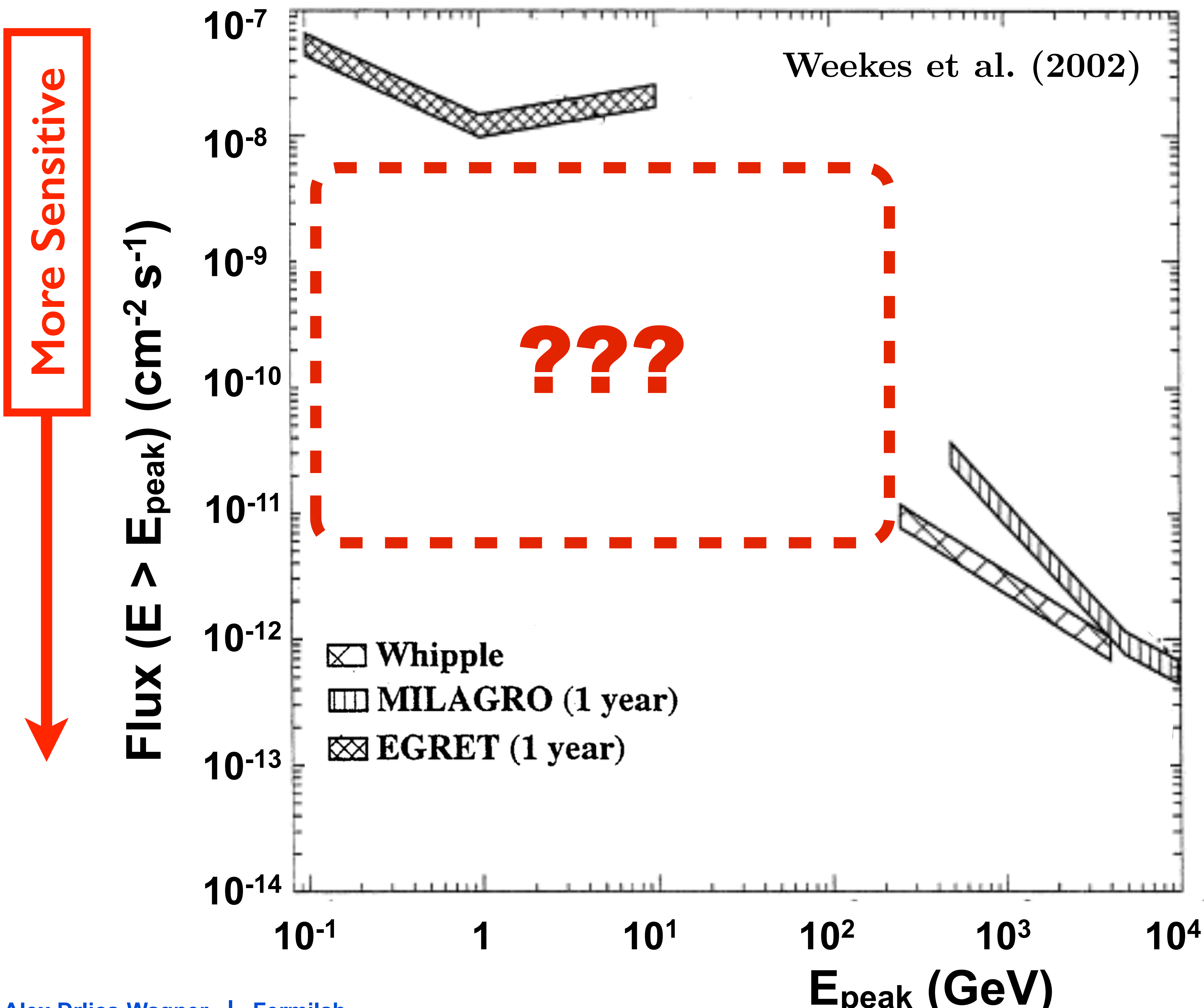


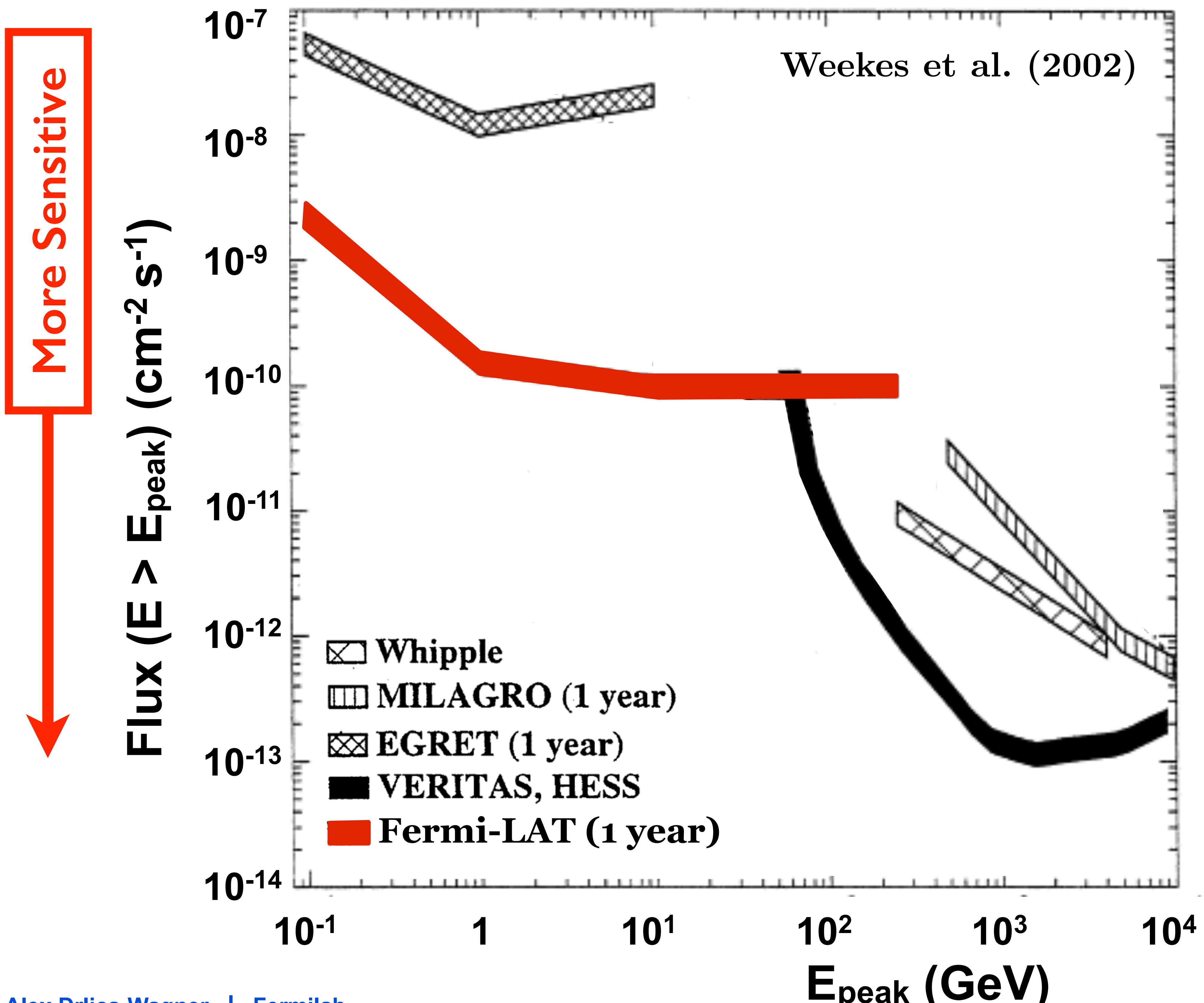
The Sun

Piere et al. Phys Rev D83, 023581 (2011)

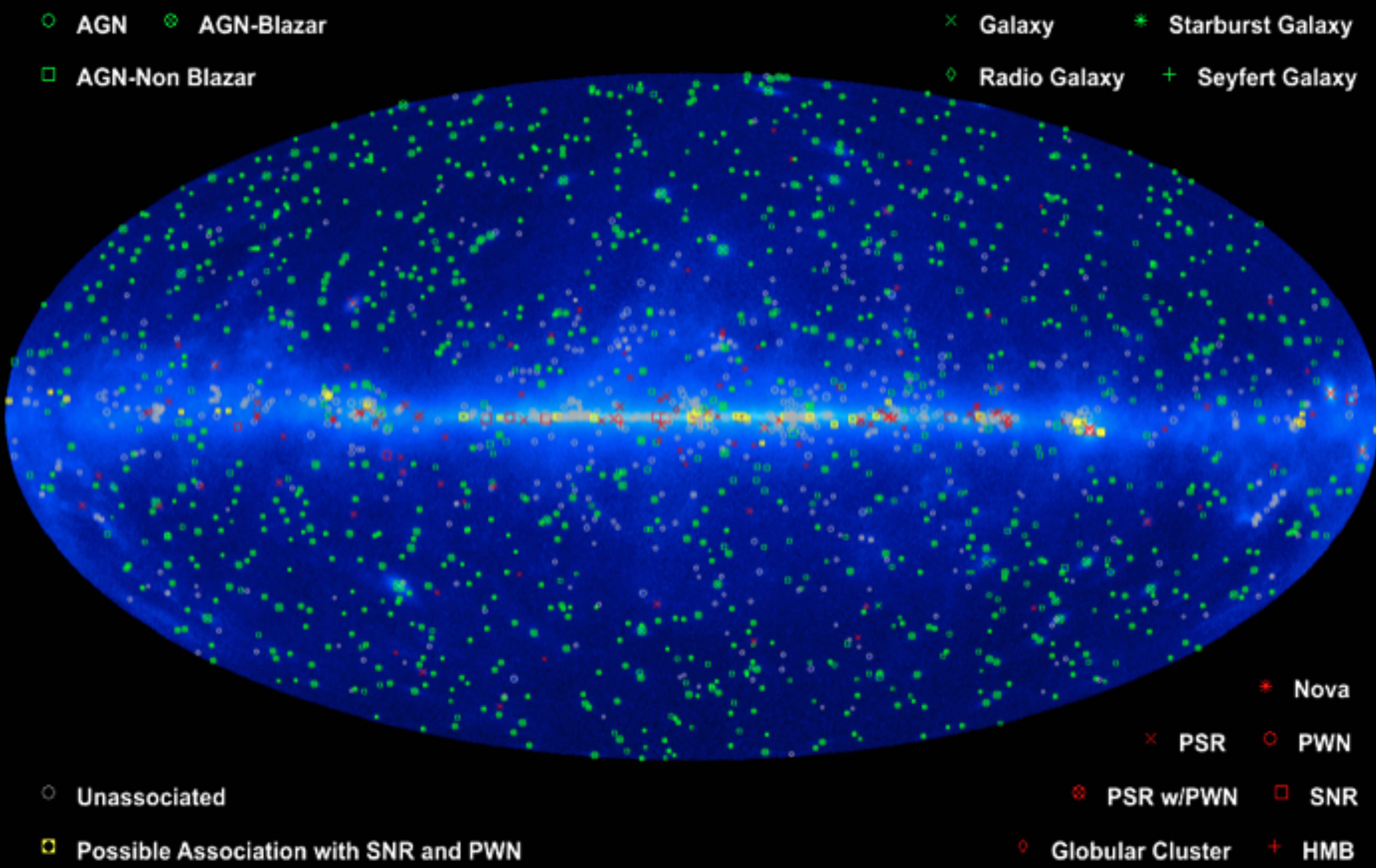
Case for the Fermi-LAT



Case for the Fermi-LAT



Fermi Large Area Telescope 2FGL catalog



Credit: Fermi Large Area Telescope Collaboration

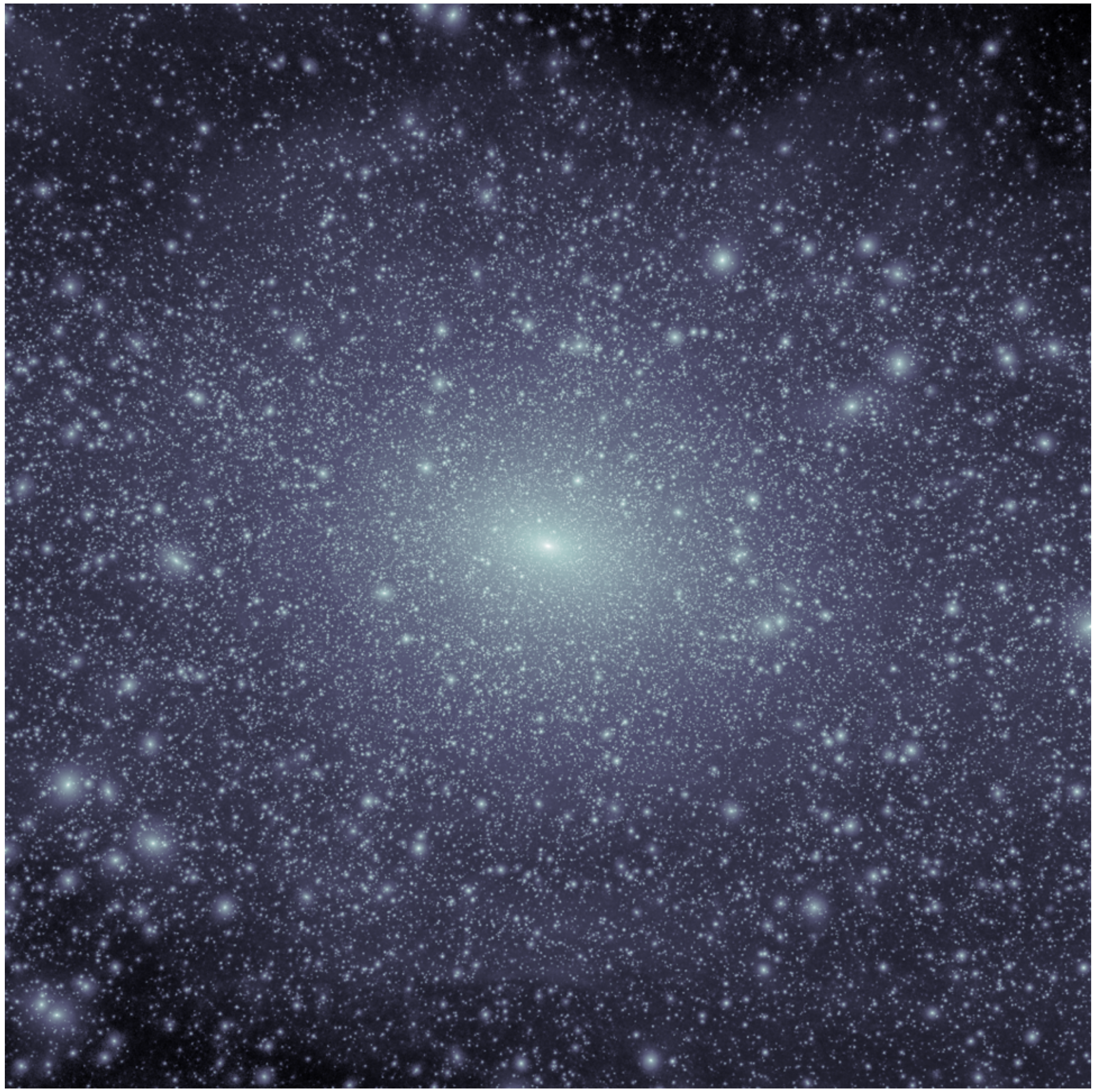
Search Strategies

1. Where is the dark matter?

2. Center of large gravitational potentials (e.g., galaxy clusters, galaxies)
   1. Large signal
   2. Known location
   3. Large astrophysical backgrounds

3. Local over-densities associated with the Milky Way
   5. Concentrated
   6. Nearby
   7. Low background

Via Lactea II Milky Way Size Halo



Diemand et al., 2008

Astrophysical Gamma-ray Production

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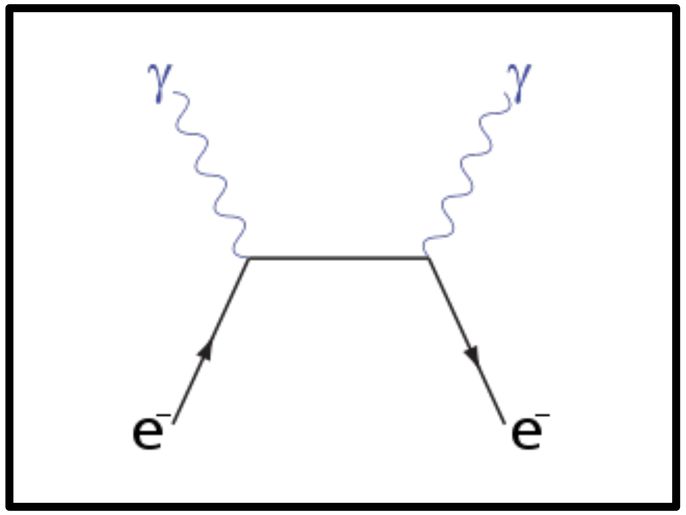

Energy Source

Accelerator

Production Mechanism

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Foreground Absorption

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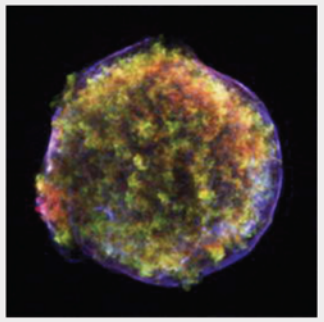
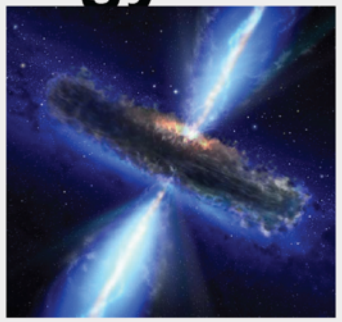
Gamma Rays

Astrophysical Gamma-ray Production

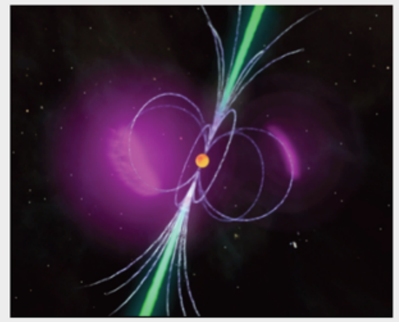
Energy Sources



Explosions

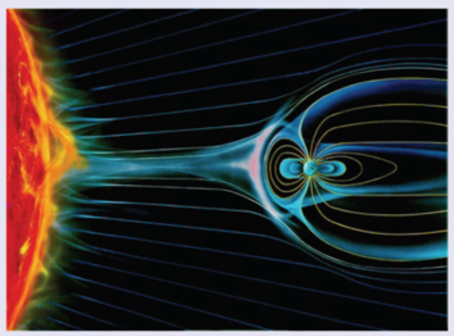


Accretion

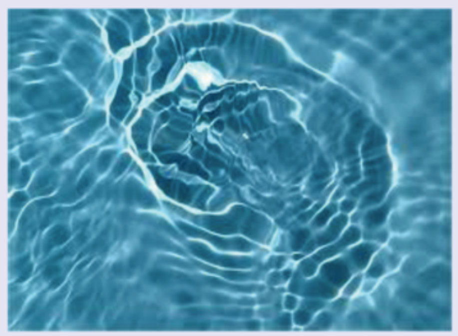


Rotating Fields

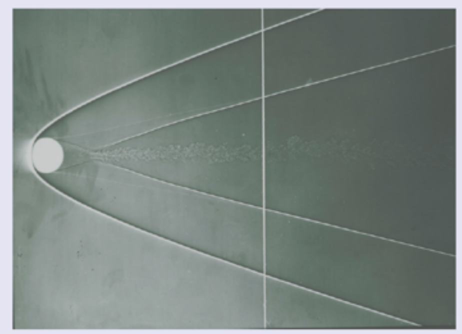
Acceleration Mechanisms



Reconnection

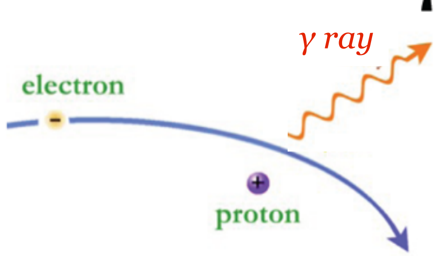


Caustics



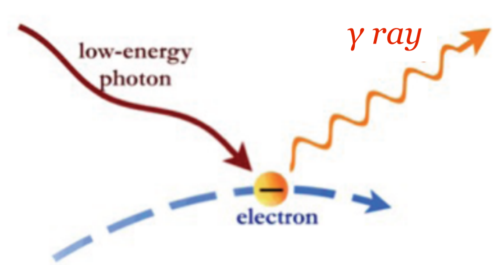
Other Shocks

γ-ray Emission Mechanisms

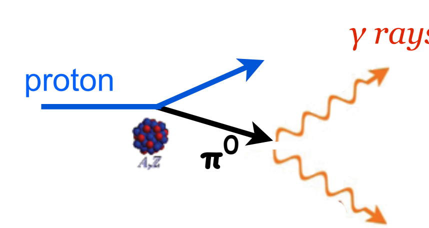


bremsstrahlung

curvature radiation



inverse Compton

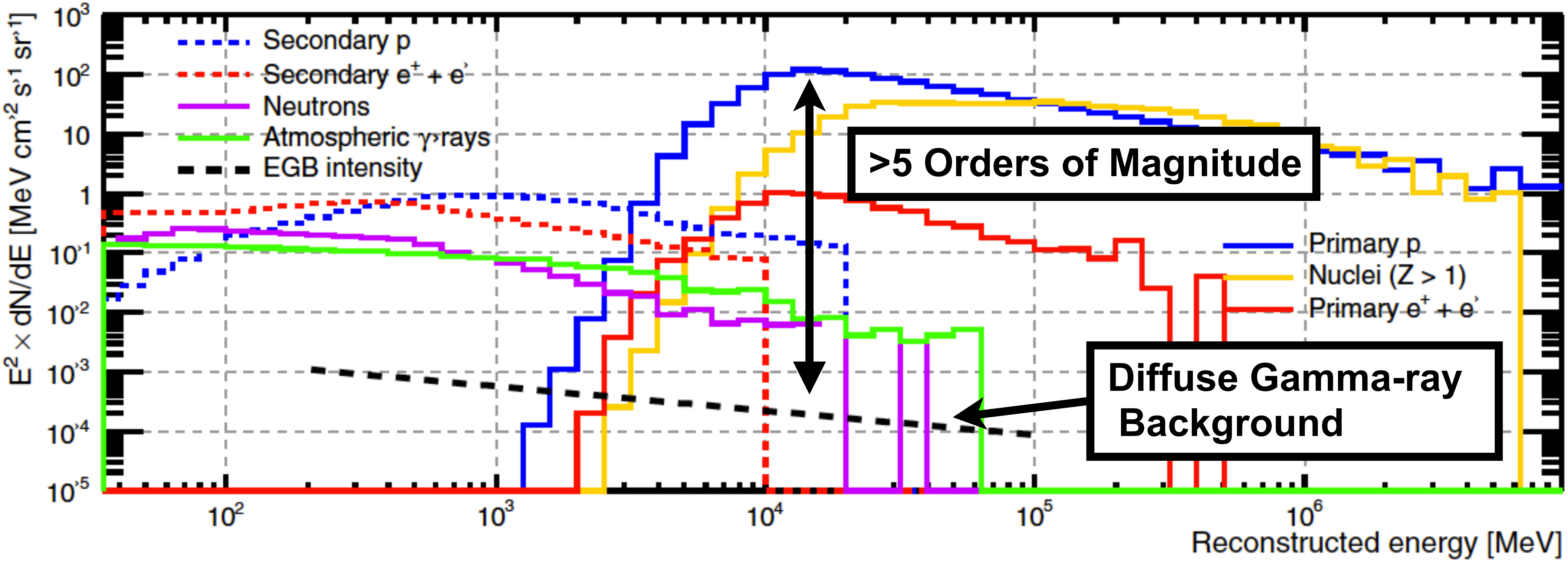


π^0 production

Astrophysical gamma-ray emission often produces radiation at other (radio, infrared, optical, X-ray, etc.) wavelengths.

Identification of gamma-ray sources is a complicated task involving the combined effort of many experiments.

Background Rejection

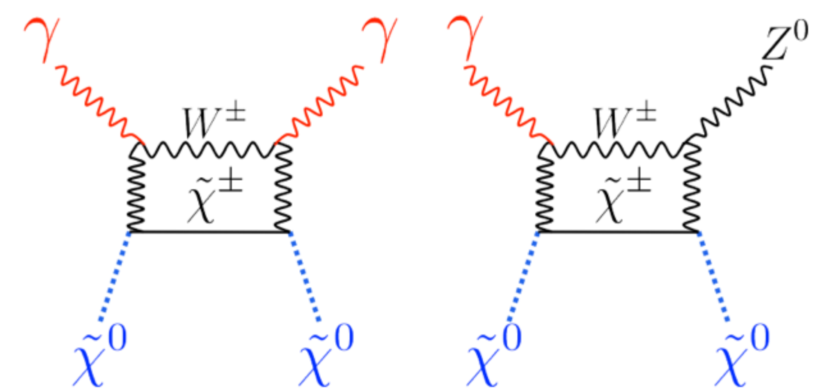


- The LAT is designed to track charged particles
- Cosmic-ray background rejection is one of the most difficult tasks
- Multi-stage background rejection developed on Monte Carlo
  - Classic cuts based analyses utilizing the ACD and other subsystems
  - Multivariate event classification through machine learning
- Harsh background rejection cuts must be validated on data

Back-up Slides:
Line Analysis

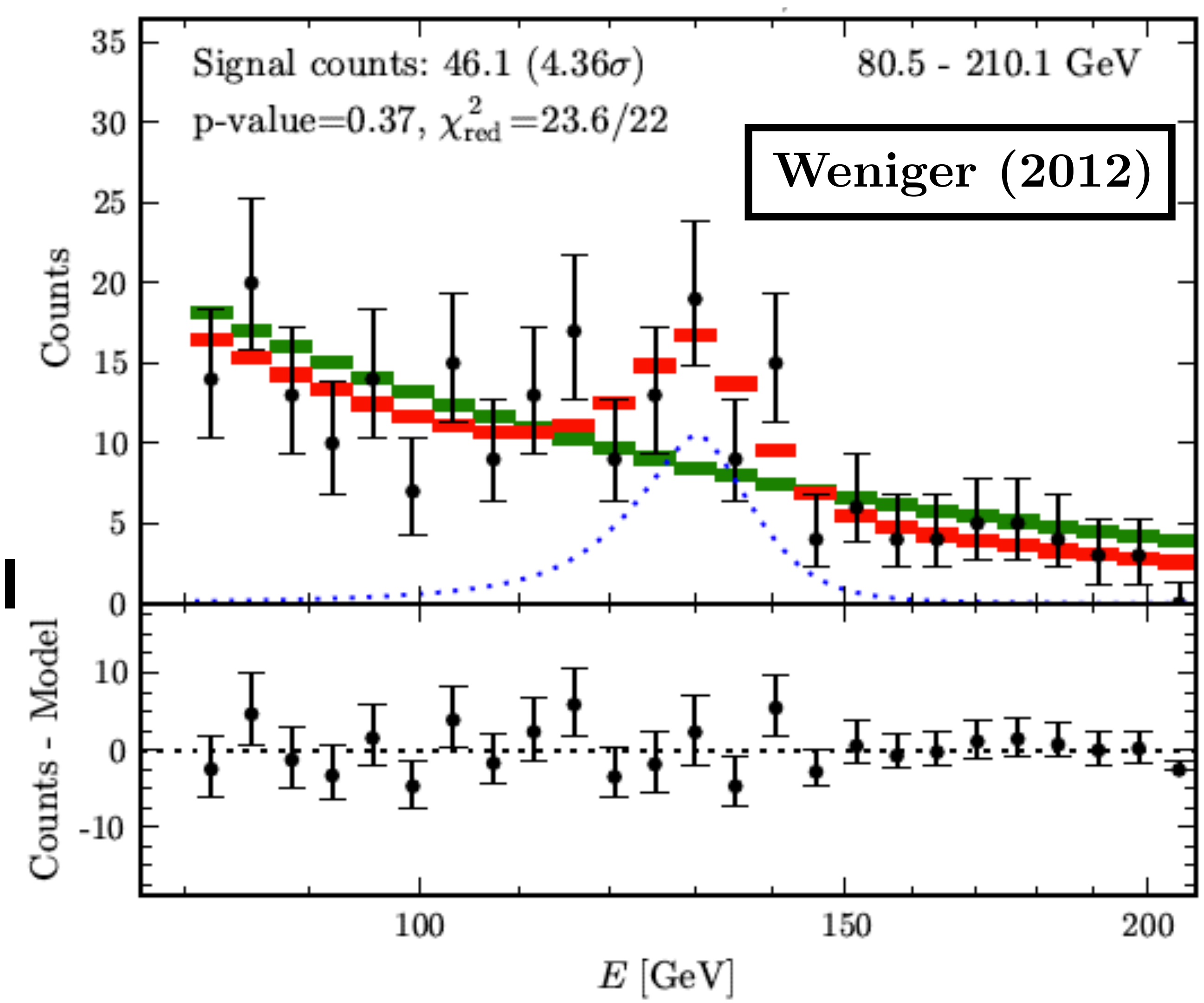
Searching for Spectral Lines

- **Annihilation into $\gamma\gamma$ or γX ($X = Z^0, H^0, \ldots$) will produce a distinct spectral feature**
  - **Clean signal**
  - **Low statistics**



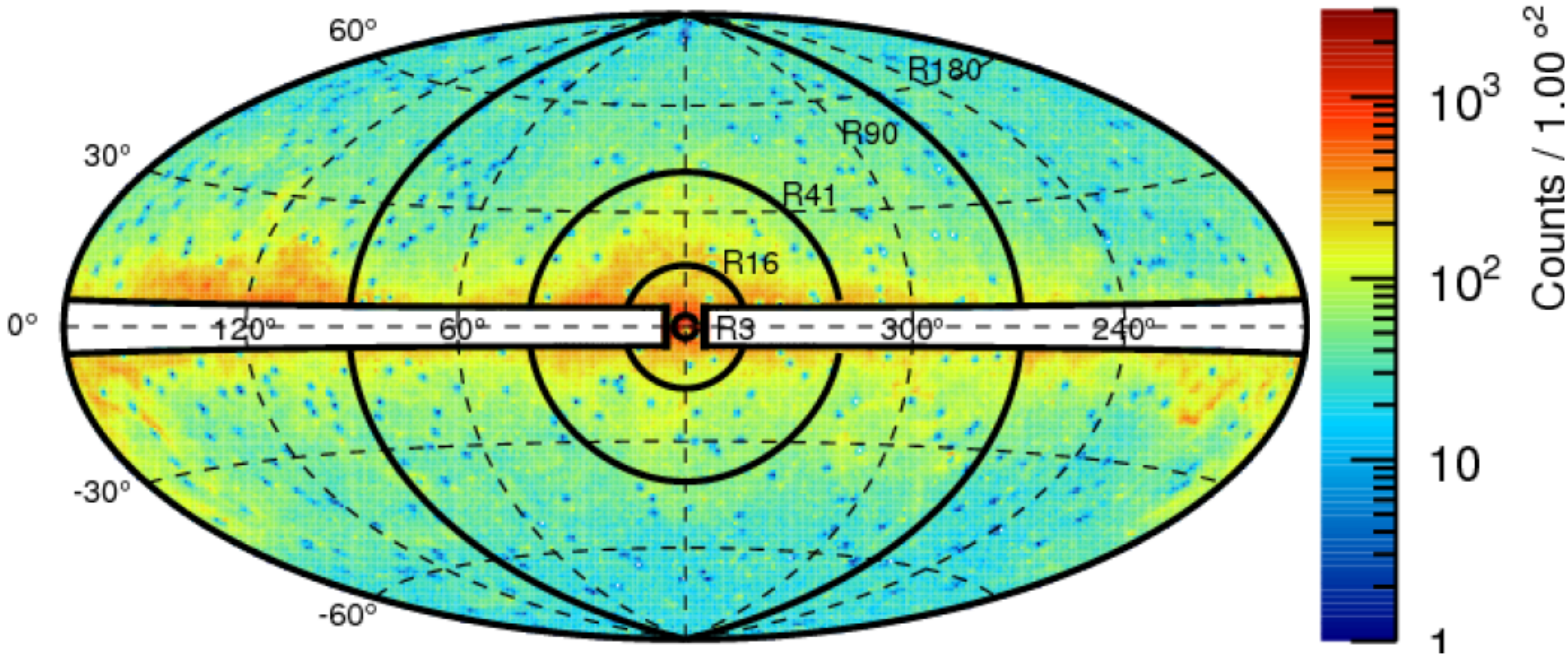
- **No significant lines in 2 years of data including the Galactic center and Galactic halo (Ackermann et al. 2012)**

- **With ~4 years of public data external authors report a >4σ (local) spectral feature at ~130 GeV (Weniger 2012)**



Optimized Regions of Interest (ROIs)

3.7 year Counts Map

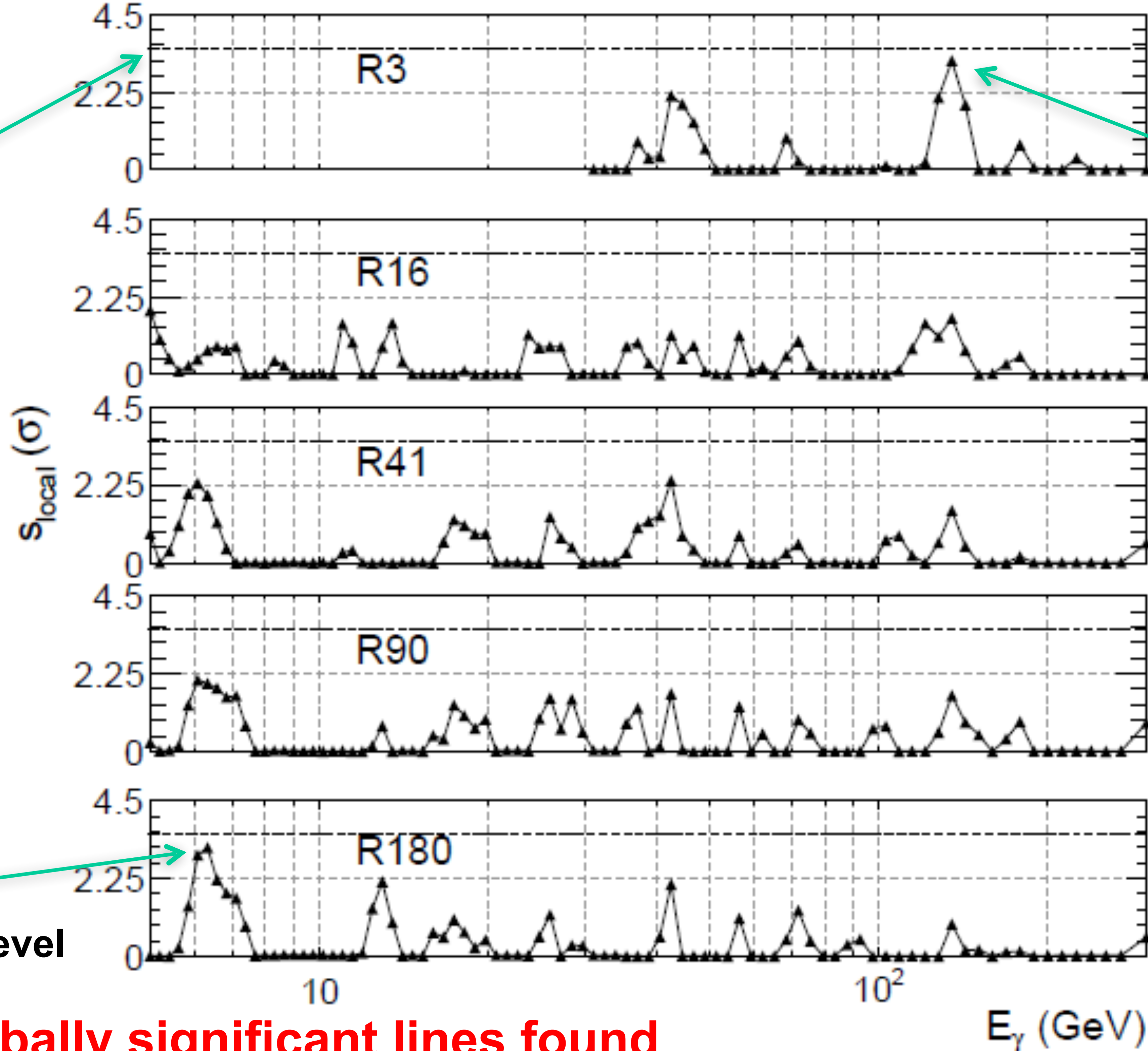


R3 (contracted NFW, no src masking)
R16 (Einasto)
R41 (NFW)
R90 (Isothermal)
R180 (DM Decay)

Ackerman et al. PRD 88, 082002 (2013)

Line Search Results

$s_{global} = 2\sigma$



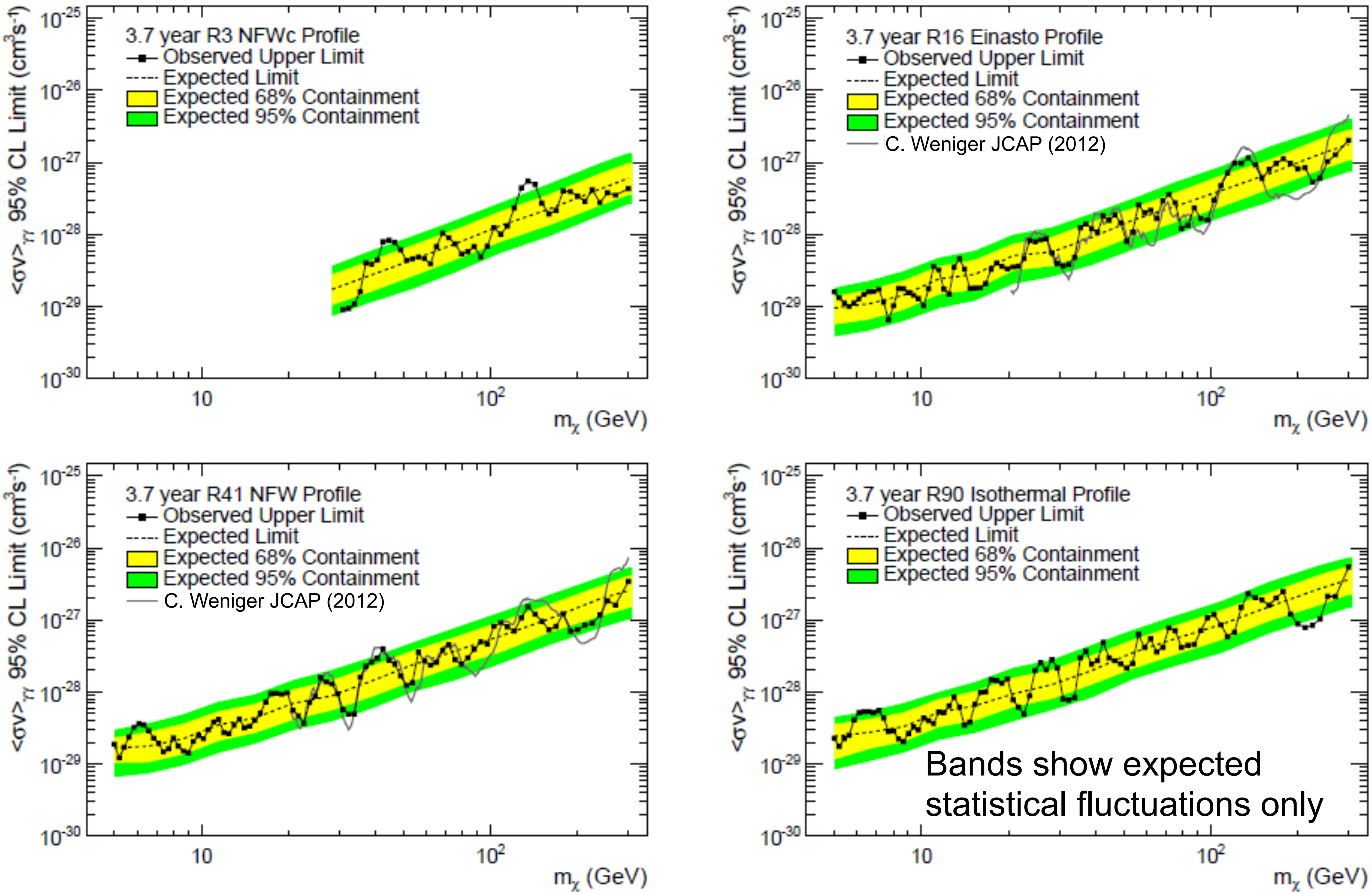
E_γ=135 GeV
$s_{local} = 3.2\sigma$
$s_{global} = 1.5\sigma$
f = 0.58
Much larger than systematic level

E_γ= 6 GeV
$s_{local} = 3.1\sigma$
$s_{global} = 1.4\sigma$
f = 0.01
At systematic level

- No globally significant lines found

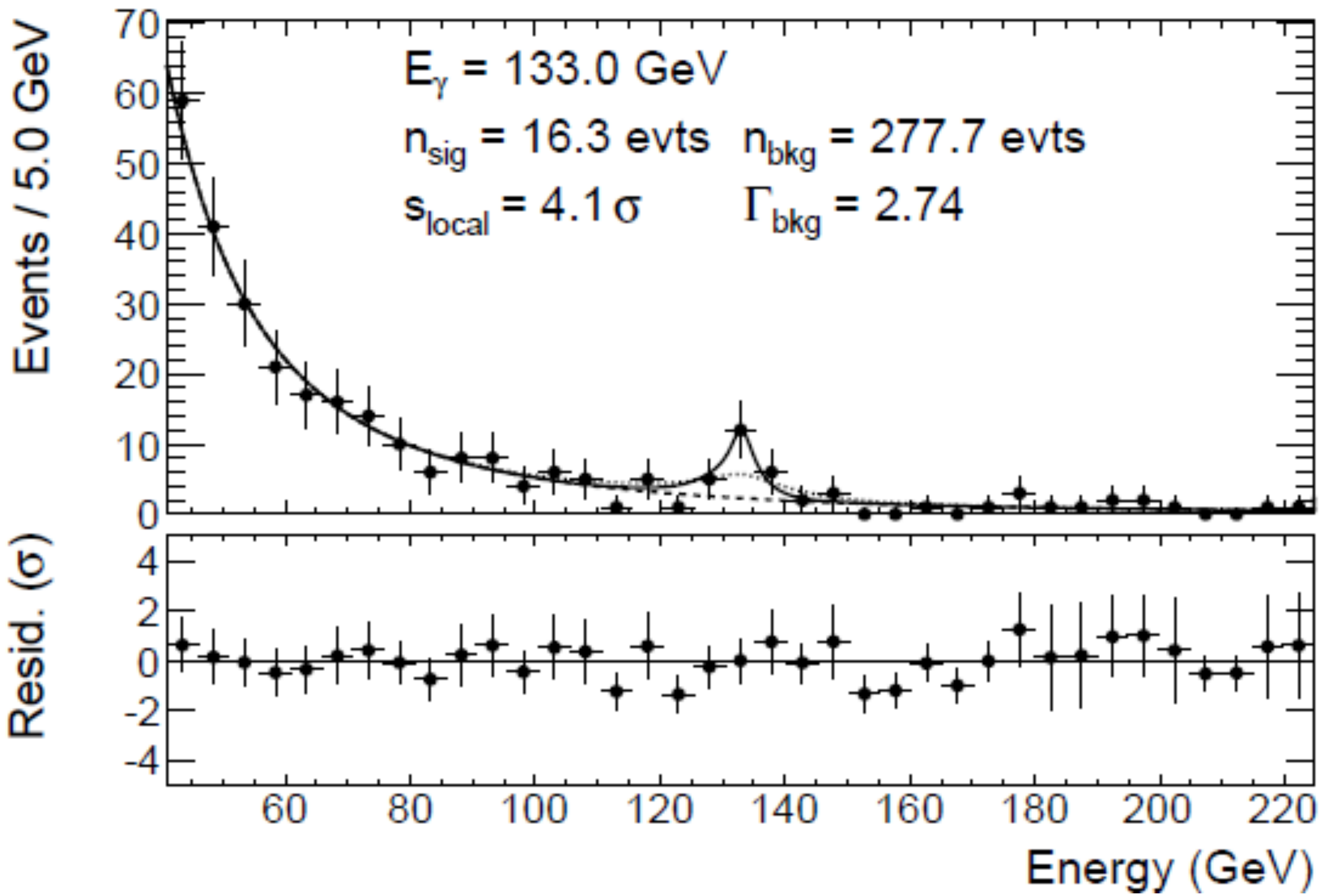
Ackerman et al. PRD 88, 082002 (2013)

95% CL <σv> Upper Limits



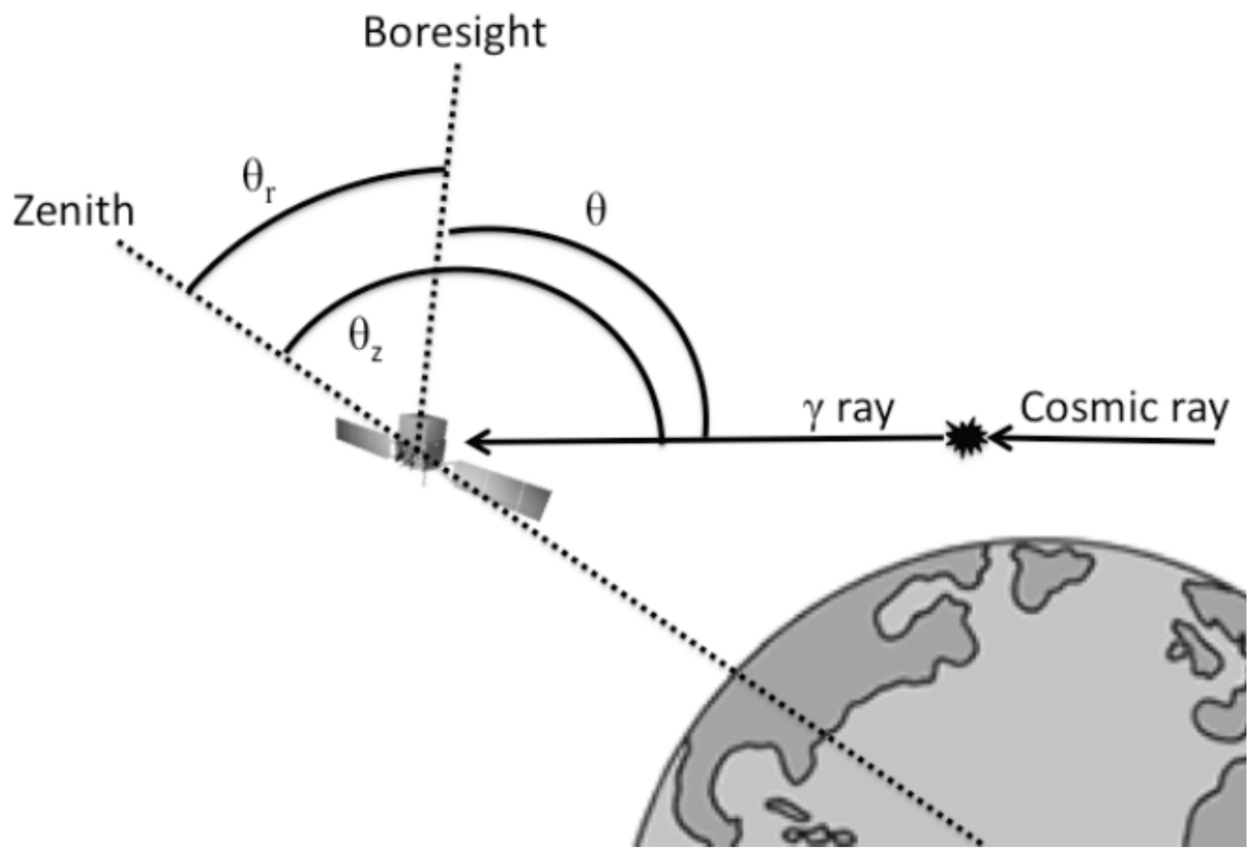
Ackerman et al. PRD 88, 082002 (2013)

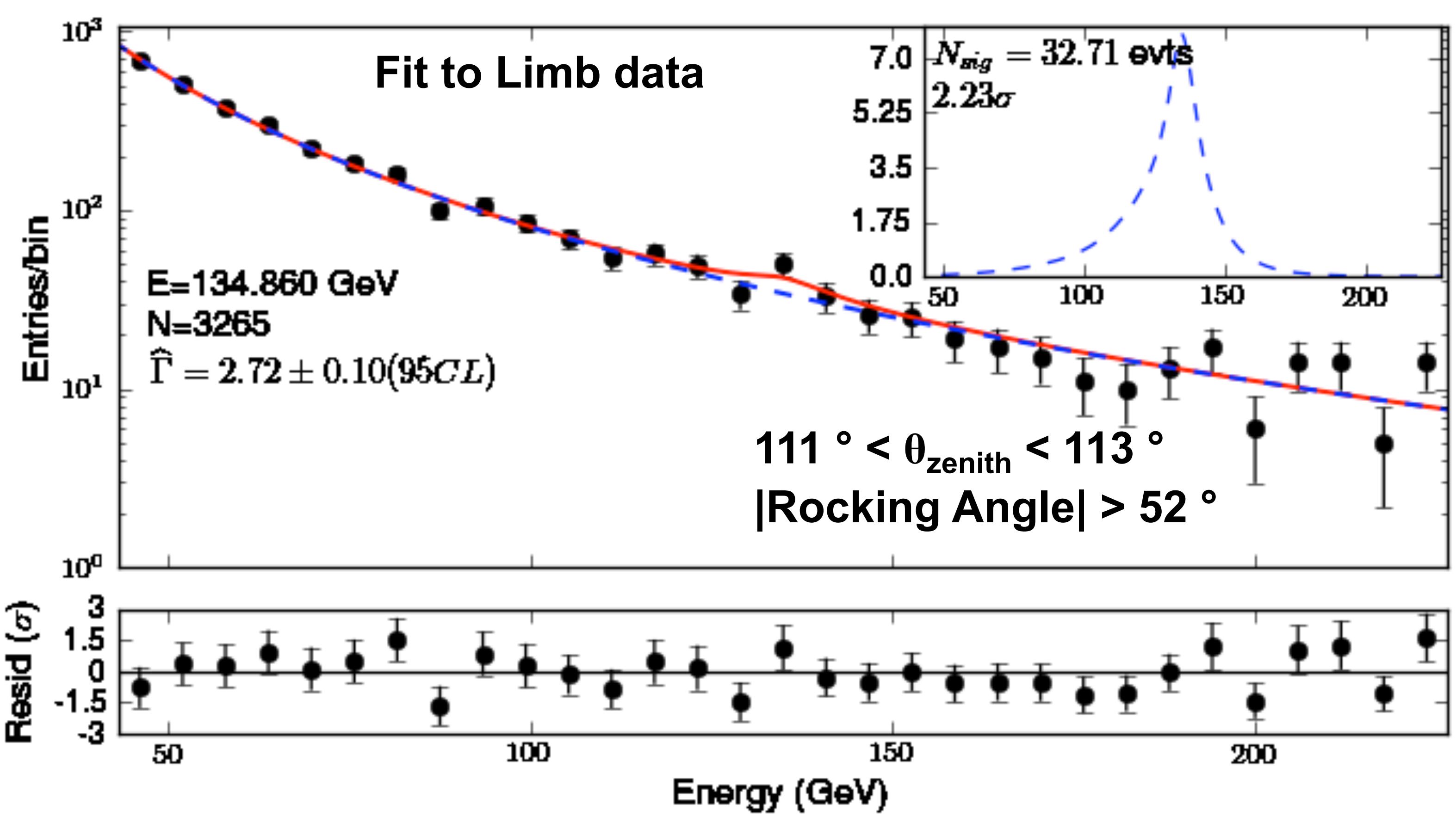
Width of 133 GeV Feature



- **Let width scale factor float in fit (while preserving shape)**
- $s_\sigma = 0.32^{+0.22}_{-0.07}(95\%CL) \quad \Delta TS = 9.4$
- **Feature is <u>significantly narrower</u> than expected energy resolution (s_σ=1)**

Earth Limb Control Sample

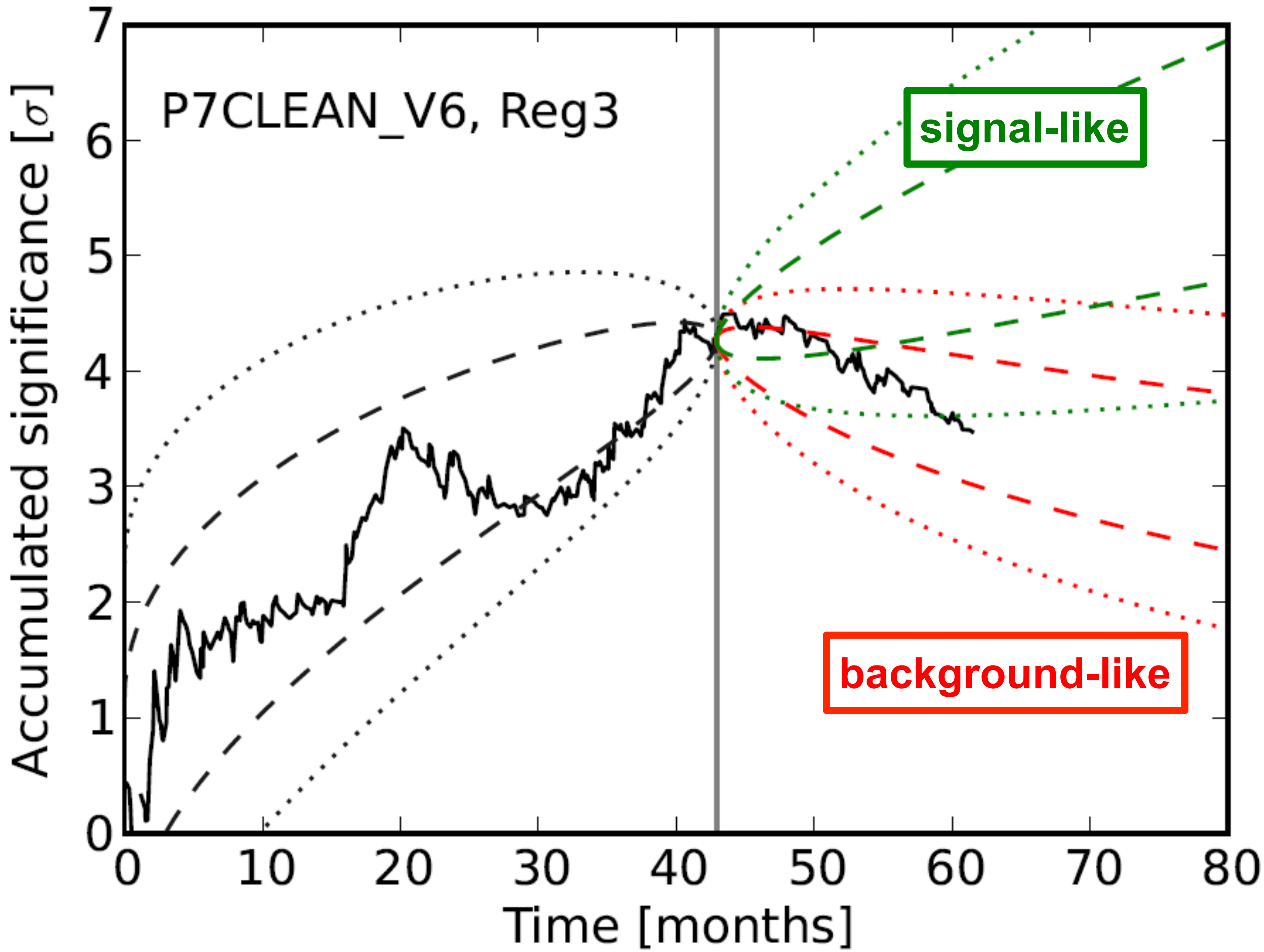




- **Earth Limb is a bright, well understood source**
  - **γ rays from cosmic-ray interactions in the atmosphere**
  - **Expect a smooth power-law**
  - **Can be used to study instrumental effects**
- **Line-like feature at at 133 GeV in the limb spectrum (2.0σ local)**
  - **Surprising since limb should be smooth (no dark matter)**
  - **S/N_{limb} ~14%, while S/N_{R3} ~ 61%**
    - **Limb feature not large enough to explain all the GC signal**

133 GeV Feature in 5.2 year dataset

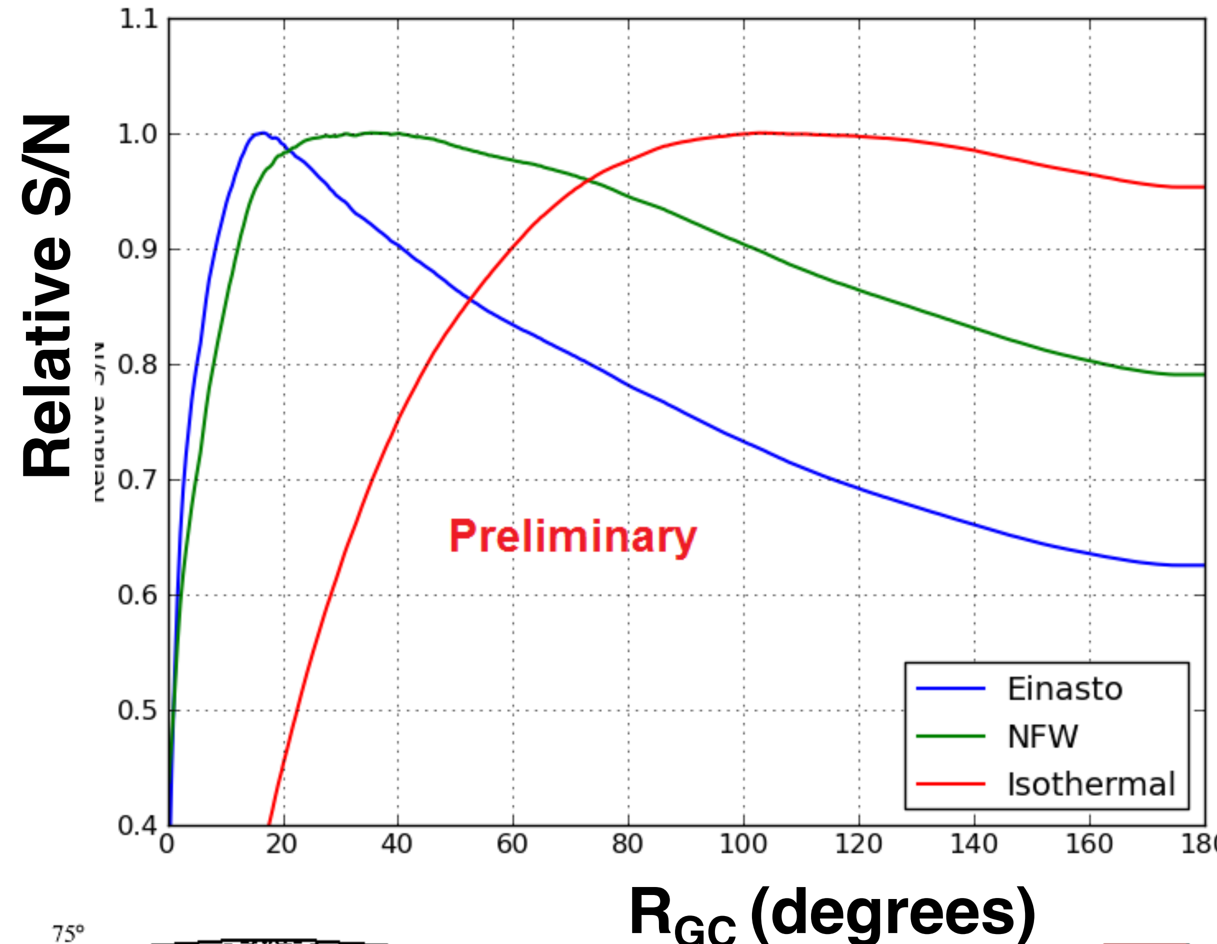
- **Since spring 2012, the significance of the feature has declined**
  - **More "background-like"**

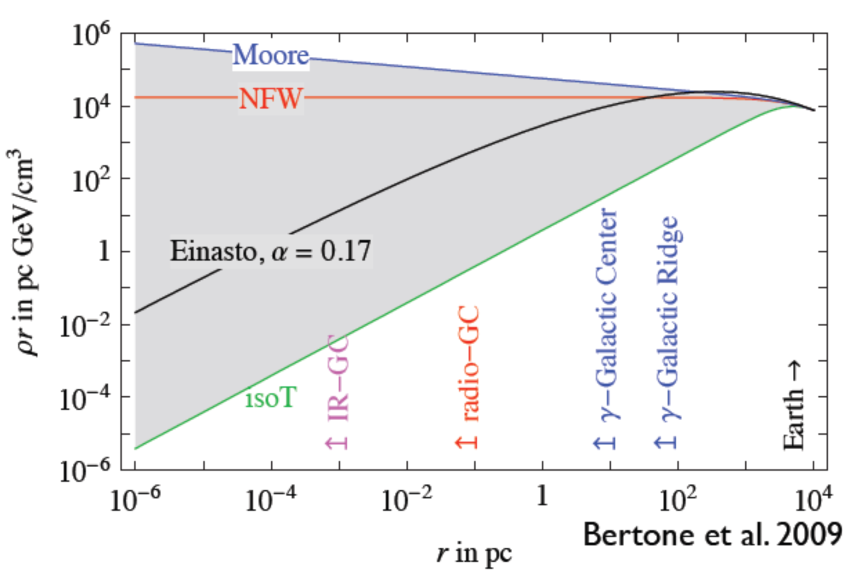


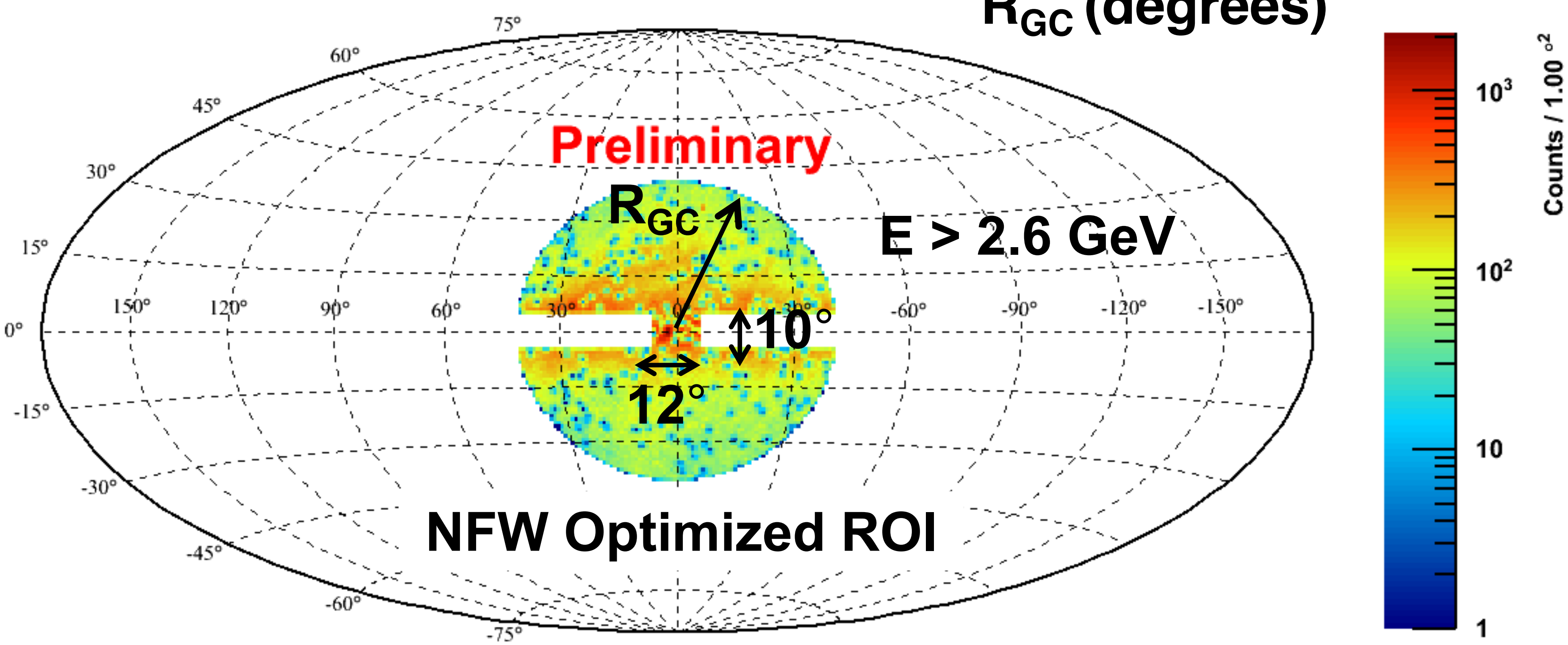
Weniger et al (2013):
http://fermi.gsfc.nasa.gov/ssc/proposals/alt_obs/white_papers_eval.html

Region of Interest (ROI) Optimization

- Many have shown ROI optimization importance in line searches
  - e.g. C. Weniger JCAP 1208 (2012) 007
- Find R_{GC} that optimizes sig/sqrt(bkg)
  - ROI choices made a priori using MC
  - sig from J factor in that ROI
  - bkg from MC simulation of galactic diffuse model
    - http://fermi.gsfc.nasa.gov/ssc/data/access/lat/Model_details/Pass7_galactic.html
- Search in 5 ROIs
  - R0 (12°x10° GC box)
  - R16 (Einasto Optimized)
  - R41 (NFW Optimized)
  - R90 (Isothermal Optimized)
  - R180 (2 year Analysis ROI)

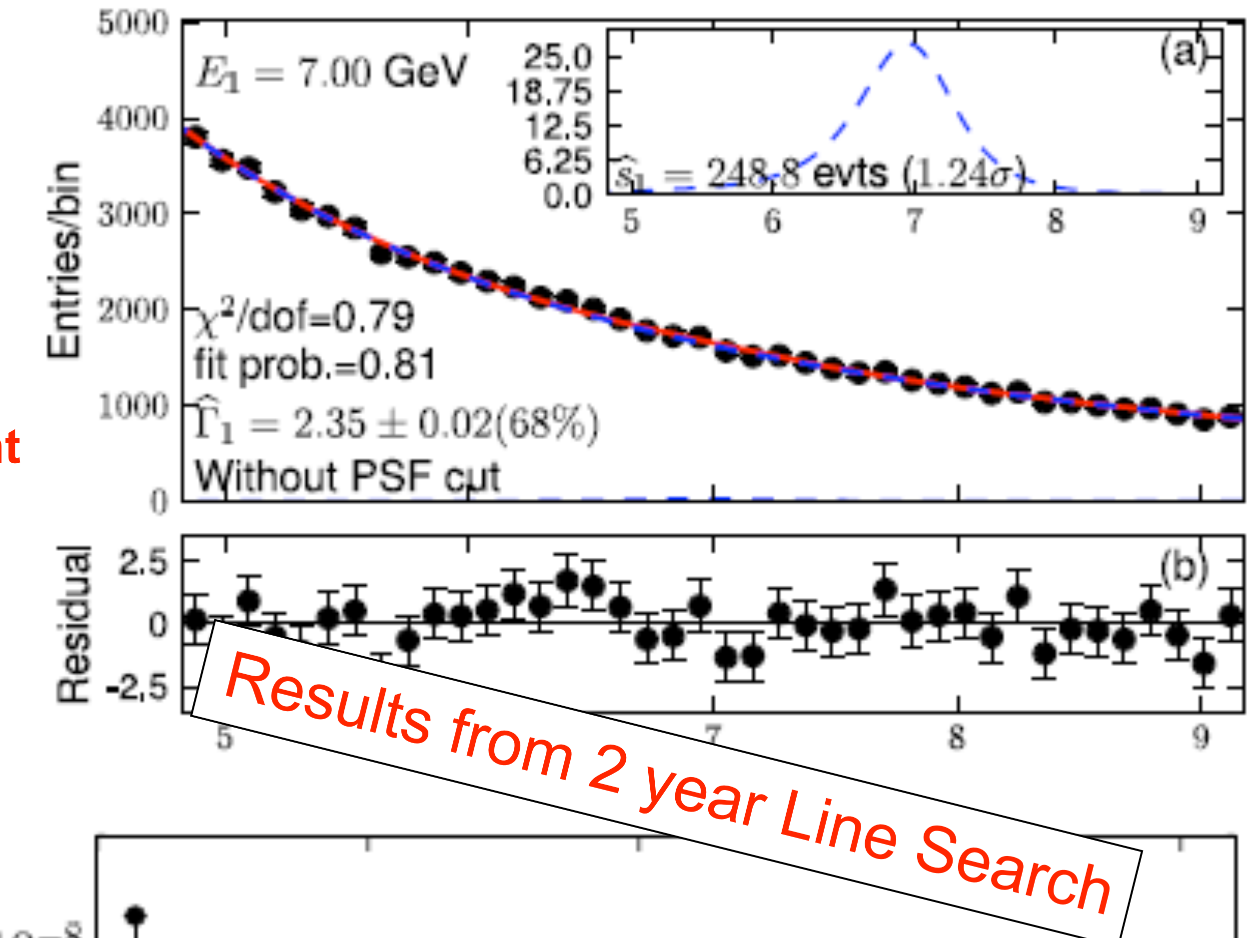


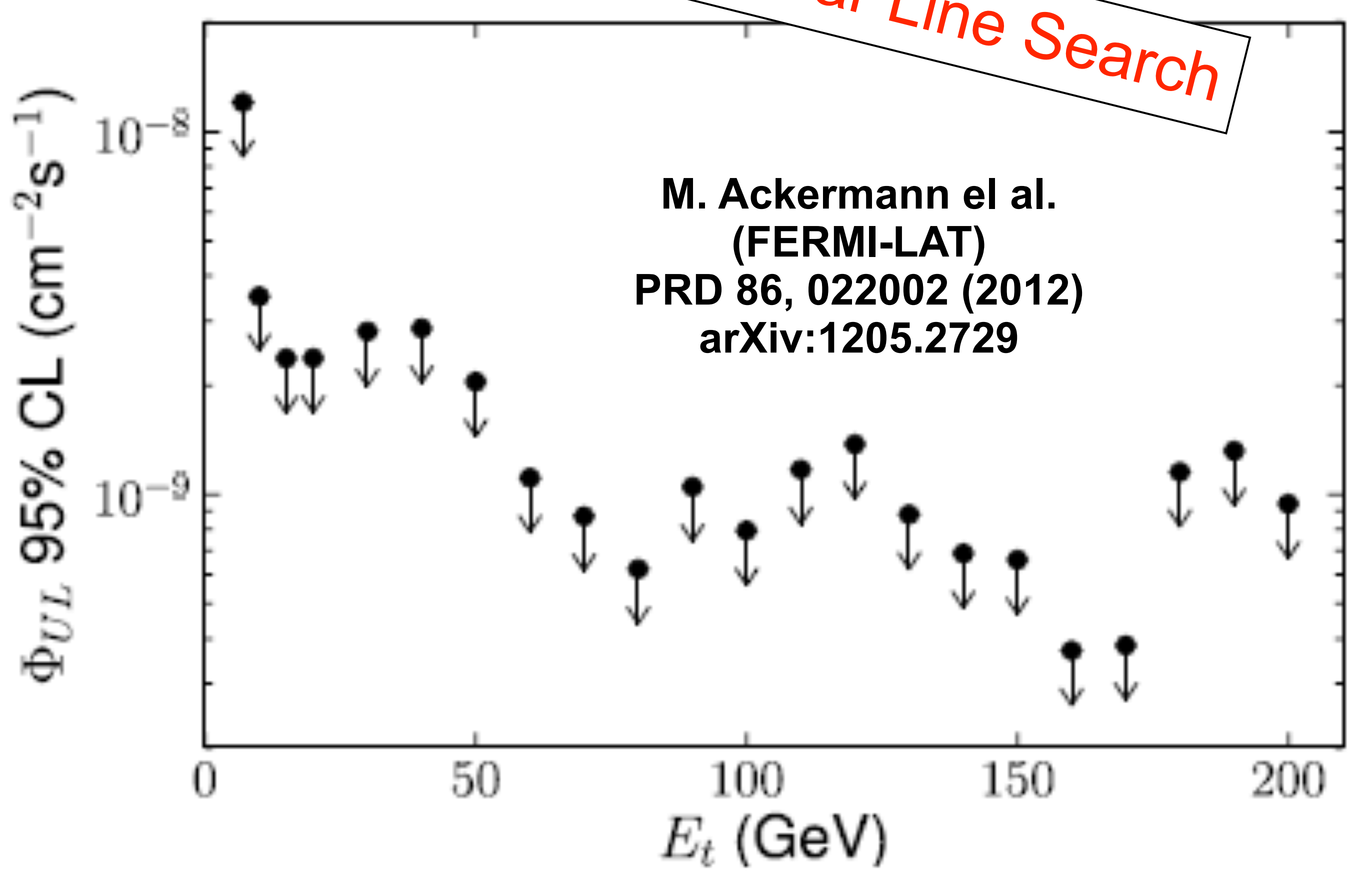




The Fermi LAT Line Search

- 2 year analysis accepted for publication in PRD
  - Current analysis uses similar method
- 4 year analysis nearing completion
  - Use Reprocessed "Pass 7 Clean" data
    - Low cosmic-ray contamination
    - Reprocessing shifts energy scale by 1-4% to account for expected accumulation of radiation damage to calorimeter
  - Plan to submit paper to PRD end of December 2012
- Search for lines from 5 to 300 GeV
  - Maximum Likelihood Fit
  - Use sliding $\pm 6\sigma_E$ windows
  - Fit for energies in σ_E steps
    - Perform finer $0.5\sigma_E$ scan near significant energies
  - Model bkg as single powerlaw
  - Γ_{bkg} and f_{sig} free in fit

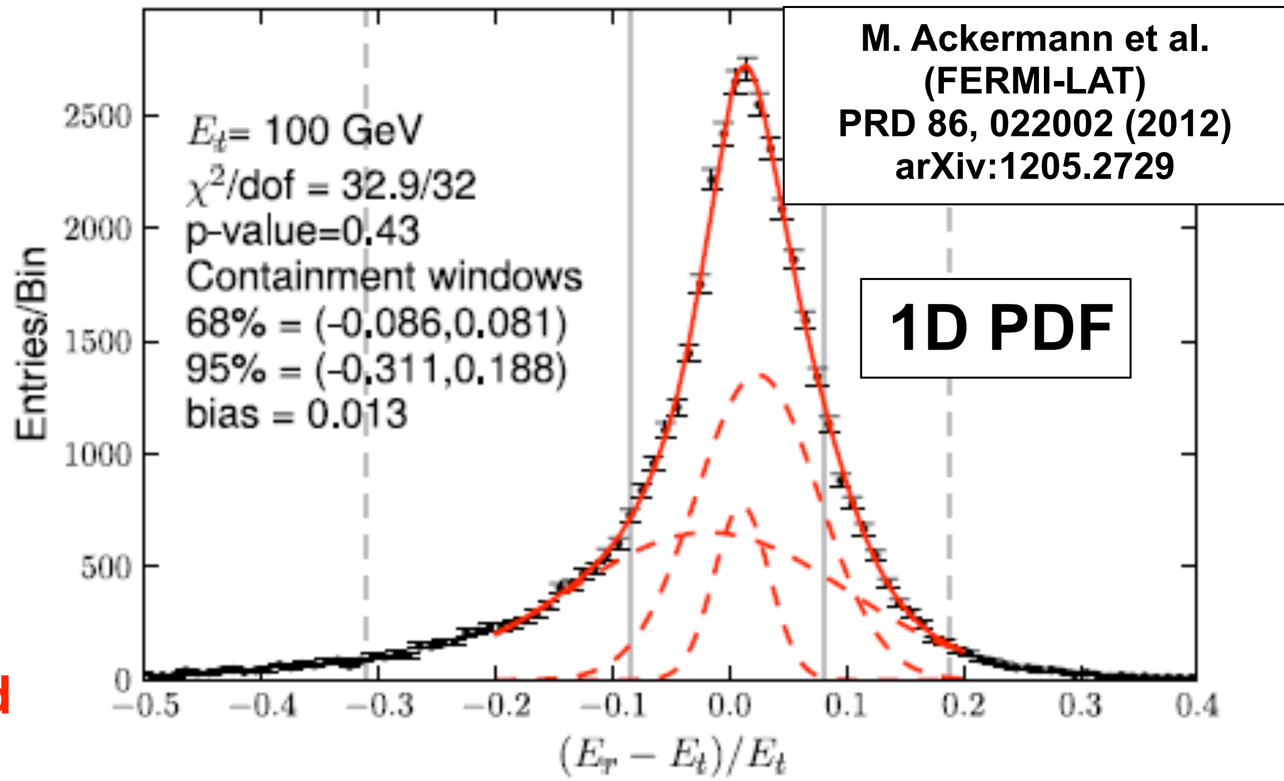


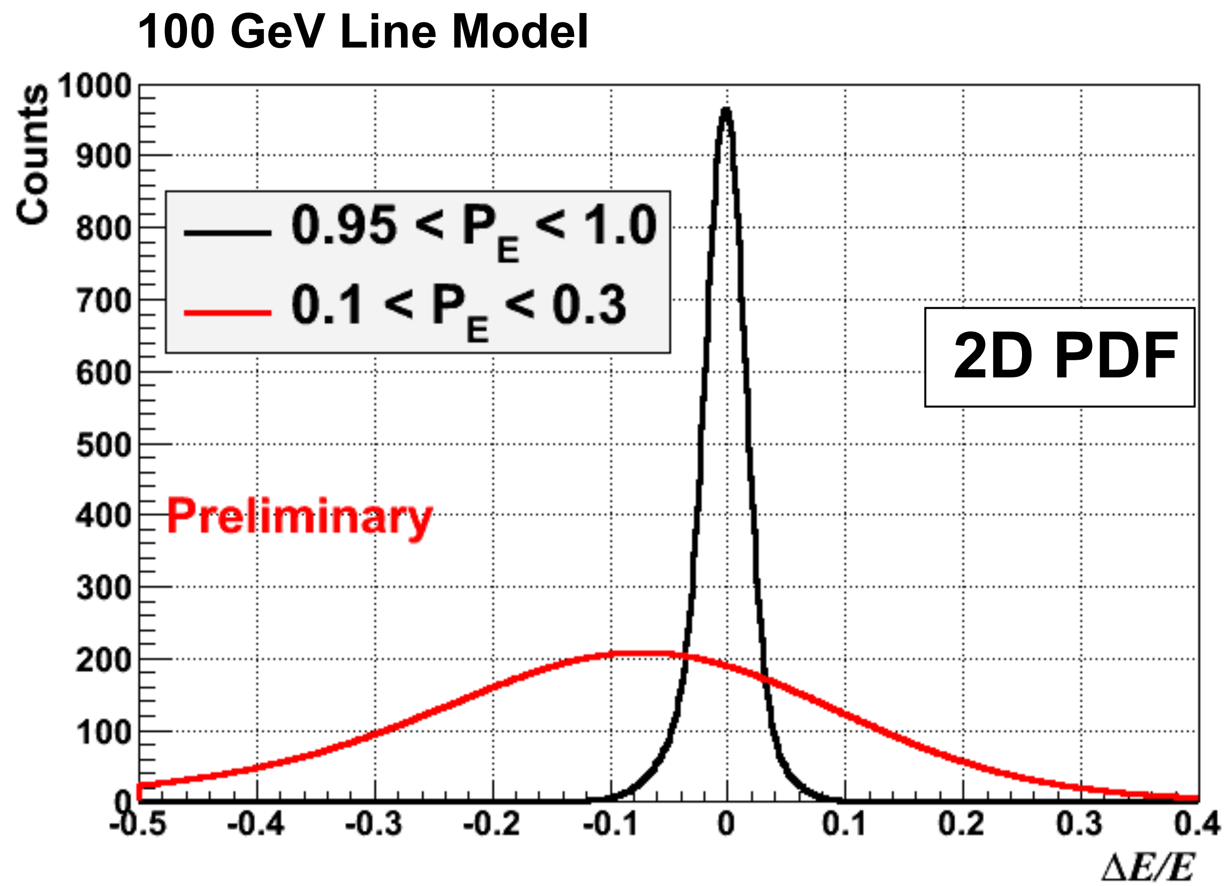


M. Ackermann el al.
(FERMI-LAT)
PRD 86, 022002 (2012)
arXiv:1205.2729

Improved Model for LAT Response to a Line

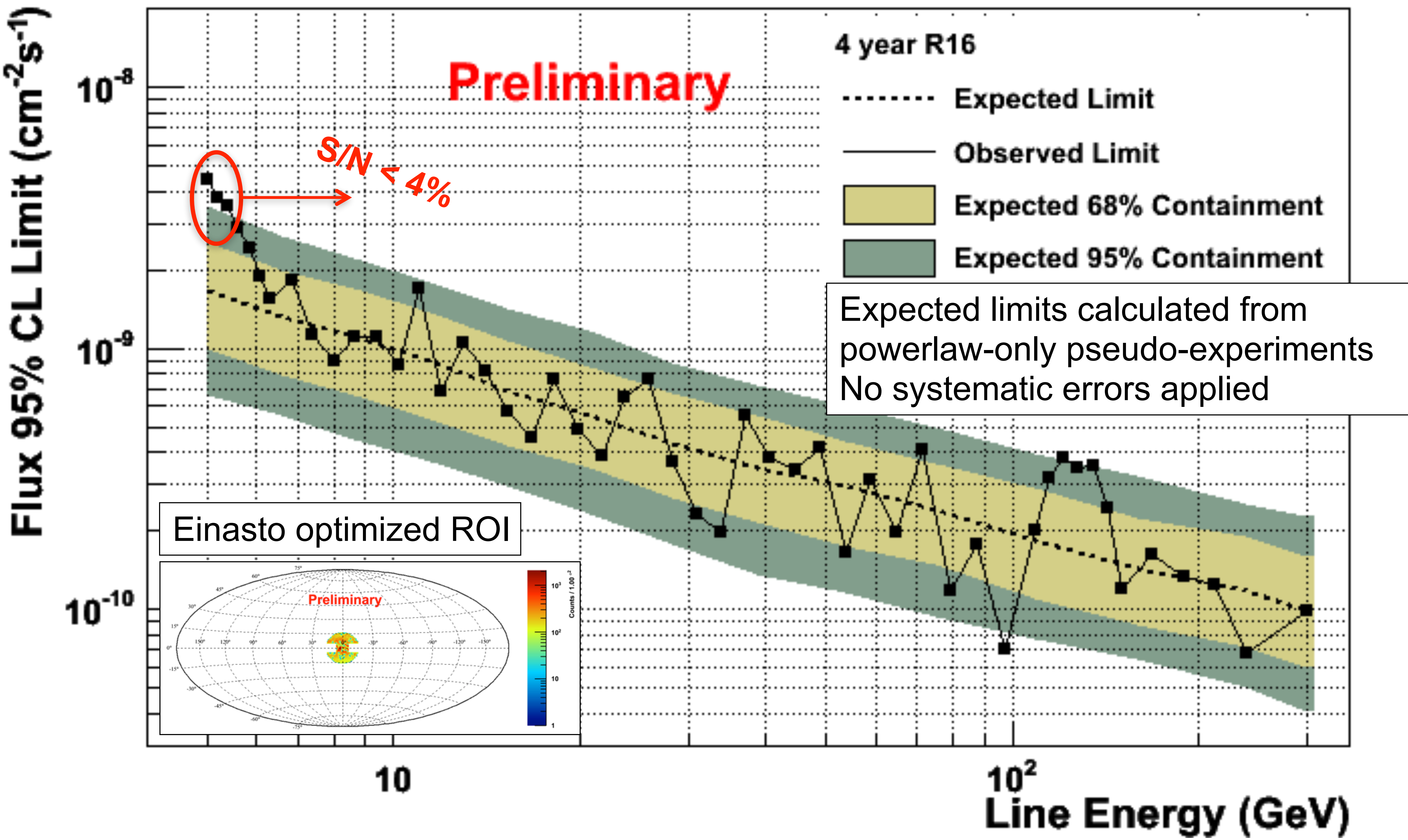
- Use full detector simulation to get Fermi LAT energy dispersion
- Previously modeled line with a triple gaussian fit ("1D PDF")
- This analysis adds a 2nd dimension to line model: P_E
  - P_E is the probability that measured energy is true energy
    - Labeled "CTBBestEnergyProb" in our extended data
  - "2D PDF" (a function of both energy and P_E)
- Break Line into 10 P_E slices and do triple gaussian fit in each slice separately
  - Fit explicitly at 9 energies and interpolate parameters in each slice to produce lines at other energies
- Including $P_E \rightarrow$ ~15% improvement to signal sensitivity (when there is signal) and counts upper limit (when there is no signal)





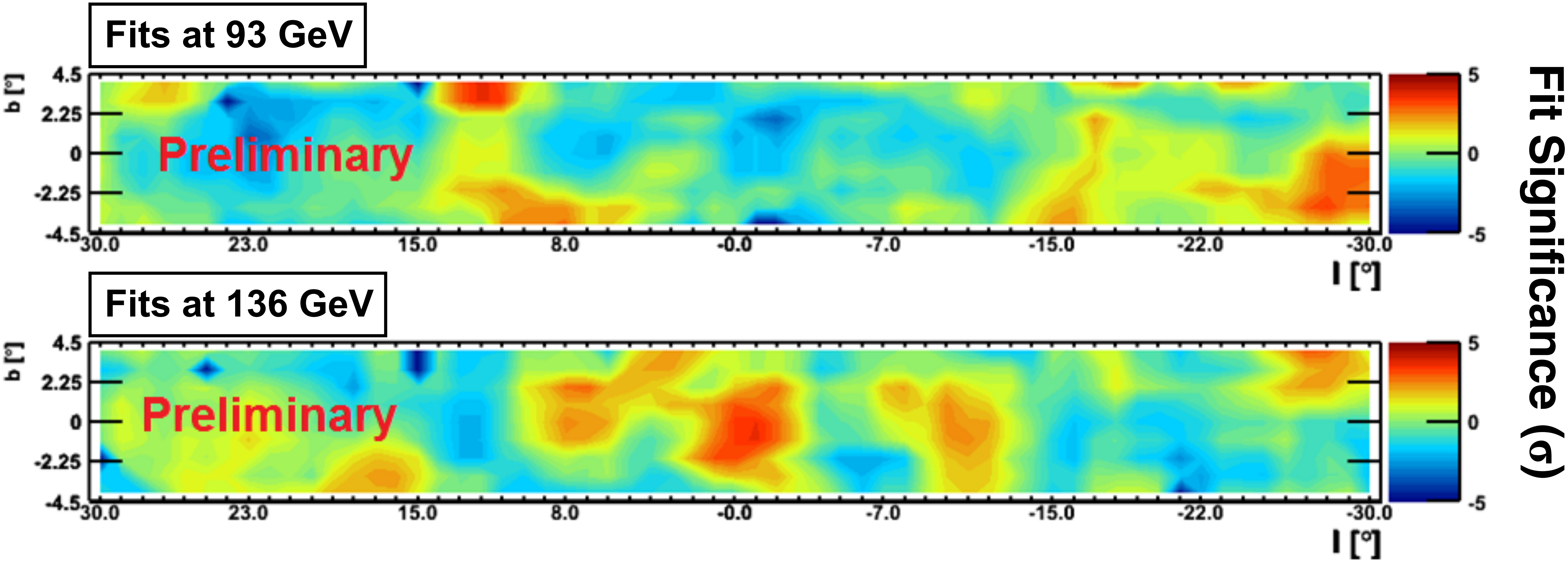
Spectral Line 95% CL Flux Upper Limit R16

- No globally significant lines found
  - Most significant fit was in R0 at 5 GeV, ~2σ (3.7σ local)

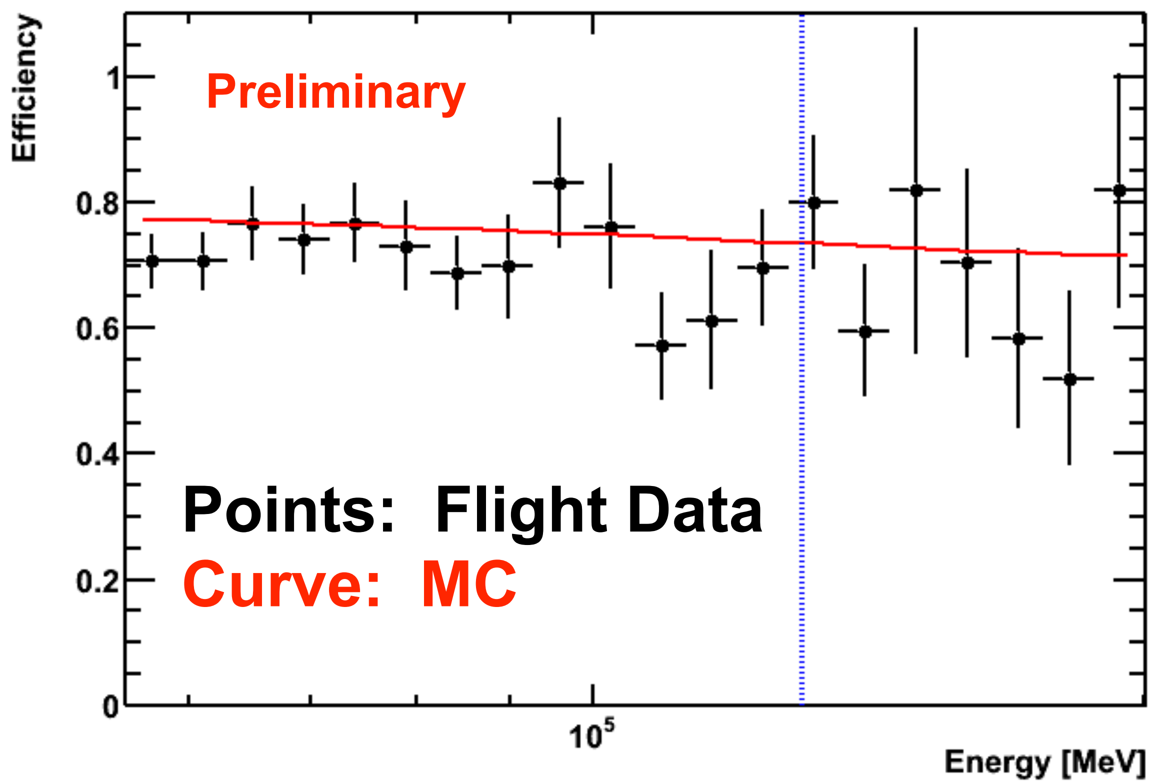


Spatial Morphology of Features in Galactic Plane

- Fit in 4°x4° ROIs along the Galactic plane in 1 ° steps
  - Fit with “1D PDF”
    - To find where the counts are coming from
    - Allowed for negative fluctuations
- Find excess near ~135 GeV near GC
  - But find similar features at other energies along the GP
  - Some indication the 135 feature not smooth, but 2-3 smaller “hot spots”
  - Excess near 135 GeV is one of the largest and near GC, but is not otherwise unique

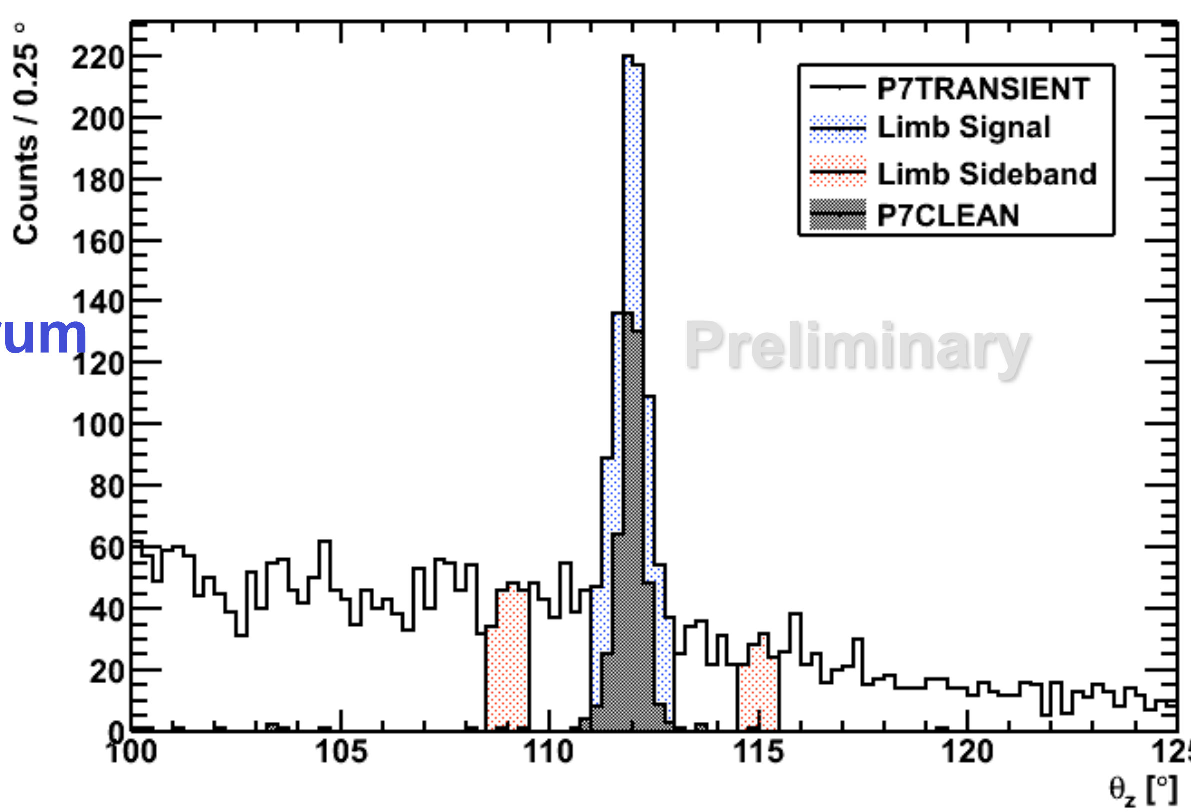


P7Transient to P7Clean Efficiency



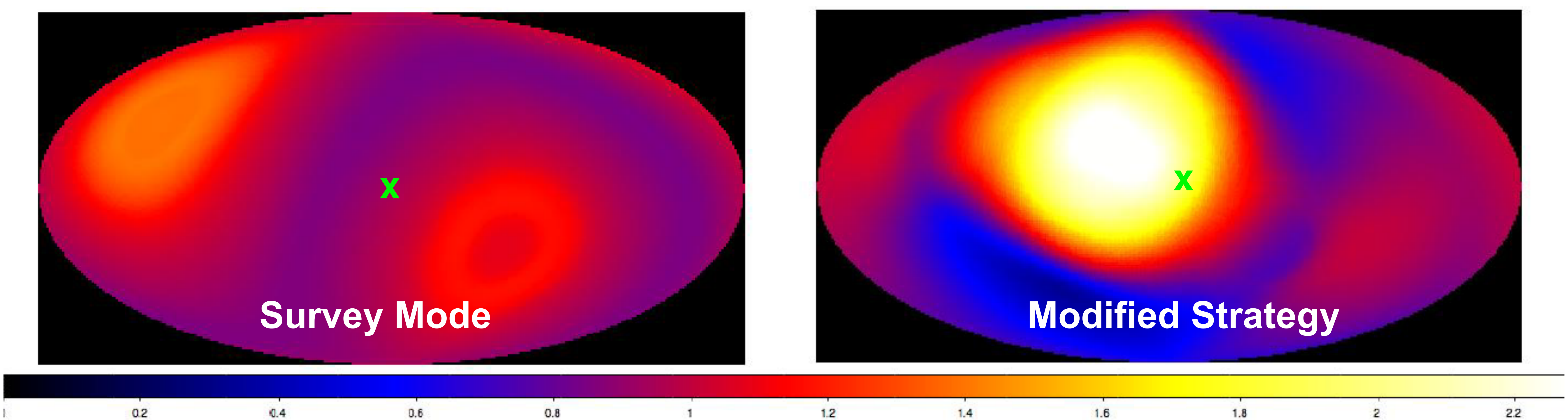
- Need to cut on times when the LAT was pointing at the limb
- Have made changes to increase our Limb datase
  - Pole-pointed observations each week
  - Extended "targets of opportunity"
    - Trace limb while target is occulted

- Dips in efficiency below and above 135 GeV
  - Appear to be related to CAL-TKR agreement
  - Could be artificially sculpting the energy spectrum



Modified Observing Strategy

- **More information can be found on the FSSC: http://fermi.gsfc.nasa.gov/ssc/proposals/alt_obs/obs_modes.html**
- **Panel discussed white paper proposals July 25th and recommended a switch to "option 4 or similar" around December 2013.**
  - **Option 4 points to keep the GC in the field of view, while still providing relatively uniform all-sky coverage**
  - **Started modified observing early December 2013**

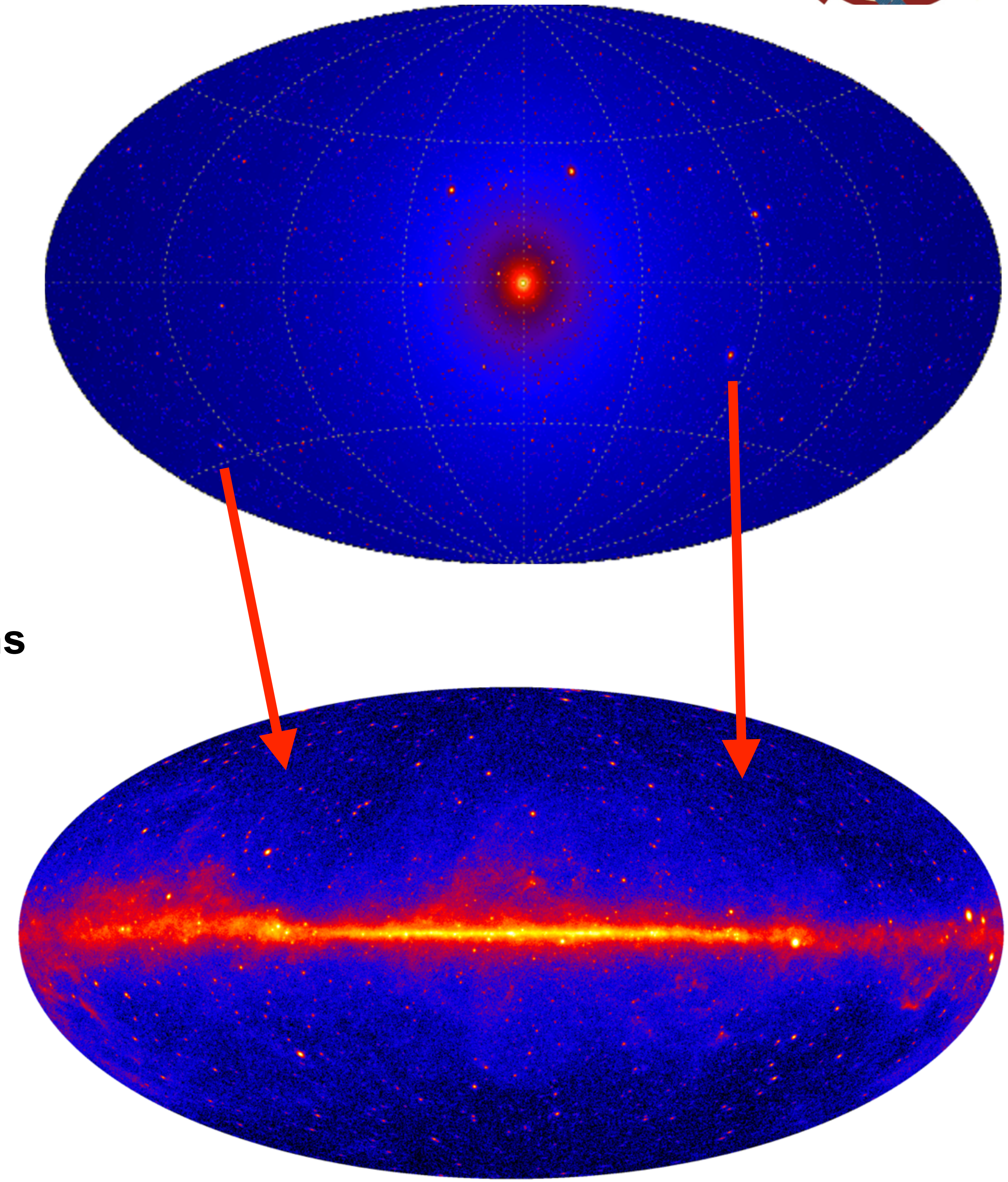


Exposure Maps

Back-up Slides:
Unassociated Sources

Dark Matter Subhalos

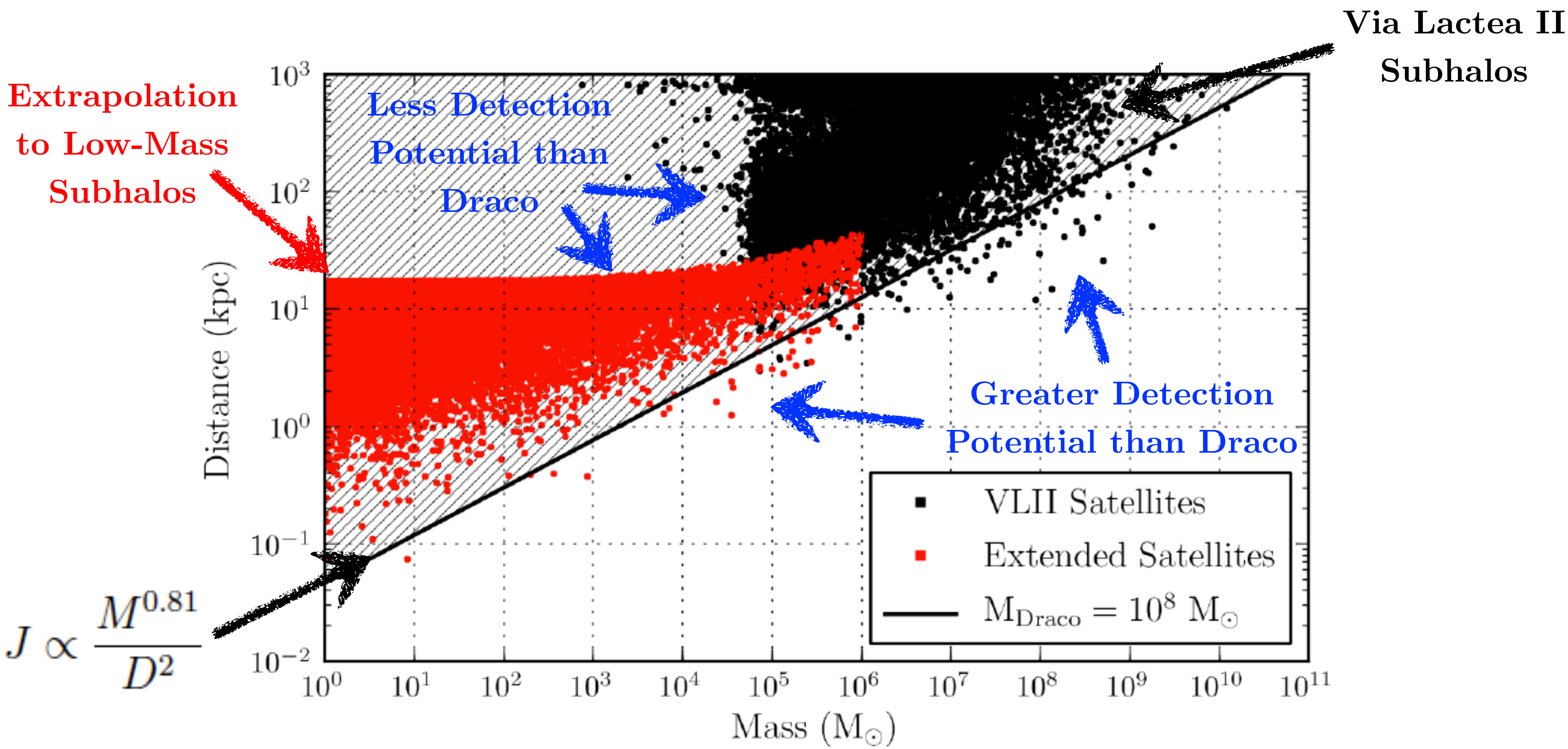
- Simulations predict that Galactic dark matter halo populated by numerous subhalos
  - Largest subhalos contain satellite galaxies
  - Smaller subhalos have no tracer in other wavelengths
- These subhalos may emit gamma-rays through dark matter annihilation
- These source would populate the gamma-ray sky and lack astrophysical associations
- Look at unassociated sources:
  - ~600 unassociated sources in the LAT catalog (most near Galactic plane)
  - Associations made through:
    - Multiwavelength observations
    - Searches for periodicity
    - Correlated variability
    - etc.



Unassociated Subhalos

ApJ 747, 121; arXiv:1201.2691

- Are dwarf galaxies the best component of substructure for dark matter detection?
- Some substructure could be more detectable than the dwarf galaxies...
- But we don't know exactly where to look...

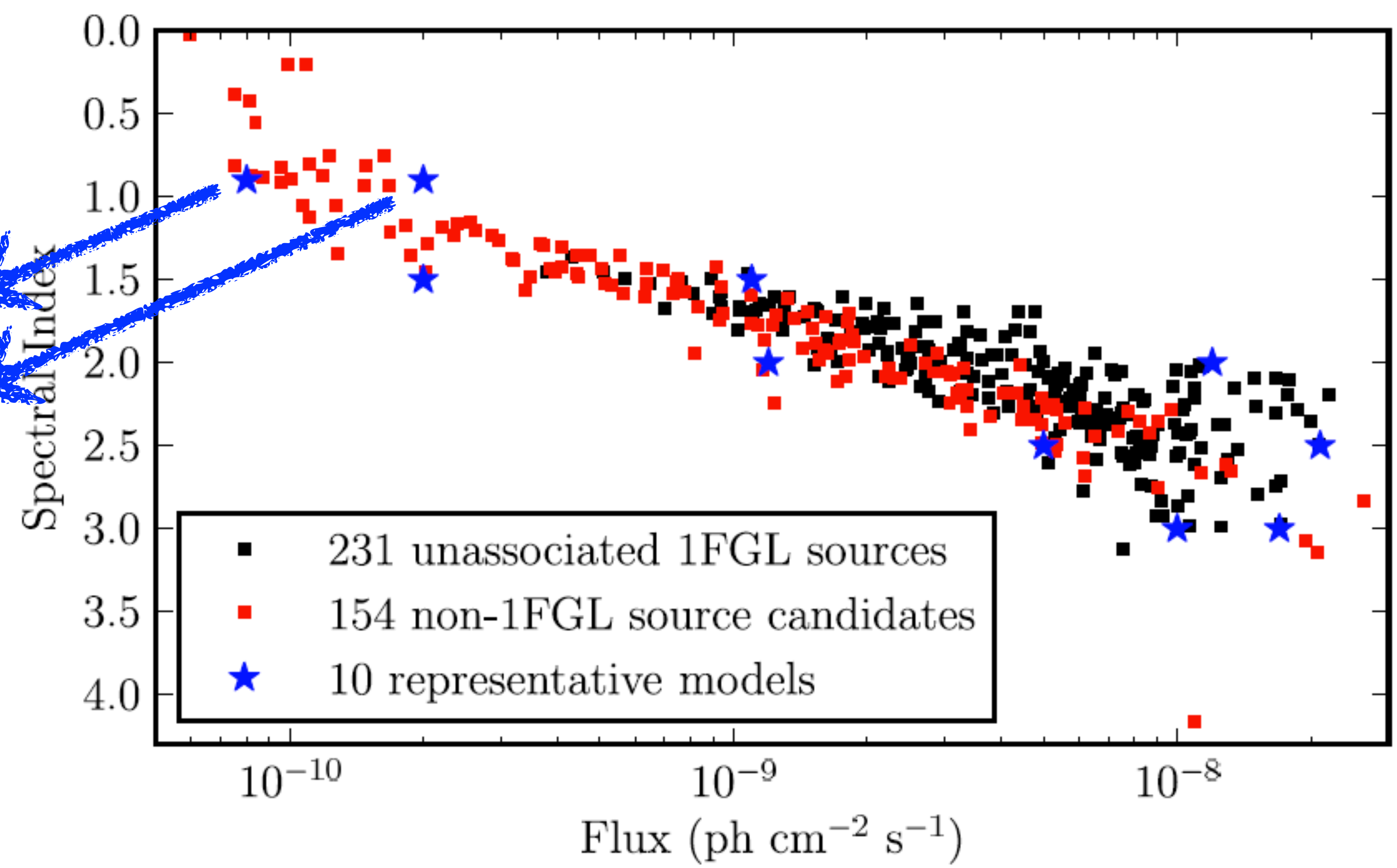


Unassociated Subhalos

ApJ 747, 121; arXiv:1201.2691

- Examine **unassociated**, high-latitude sources in First LAT Catalog.
- Search for **non-power-law** sources with that may have been missed.
- Test for **spatial extension** and **spectral shape** with 99% confidence.

Spectral Index	Flux $(\mathrm{ph\,cm^{-2}\,s^{-1}})$	TS^{99}_{ext}	TS^{99}_{spec}
0.9	2.0×10^{-10}	6.18	2.38
0.9	8.0×10^{-11}	7.87	2.46
⋮	⋮	⋮	⋮



Two Extended Source Candidates

ApJ 747, 121; arXiv:1201.2691

Radio Pulsar

Source ID	l, b (deg)	Flux (10^{-9} ph cm^{-2} s^{-1})	α_0 (deg)	TS_{ext}	TS_{spec}
1FGL J1302.3−3255	305.58, 29.90	2.46 ± 0.42	1.2	9.3	4.6
1FGL J2325.8−4043	349.83, -67.74	2.56 ± 0.39	1.3	13.2	-19.1

Two AGN

- **Two candidate extended sources**
  - **1FGL J1302.3-3255 subsequently associated with a radio pulsar**
  - **1FGL J2325.8-4043 does not pass the spectral selection and is resolved as two sources in 2FGL (high probability of AGN association)**

- **Neither source satisfies our criteria for a dark matter satellite candidate.**

NO VALID CANDIDATES IN 1 YEAR OF DATA

Unassociated Subhalos Summary

ApJ 747, 121; arXiv:1201.2691

- **Use N-body simulations to determine the probability of having no subhalos pass selection criteria as a function of $\langle\sigma v\rangle$**

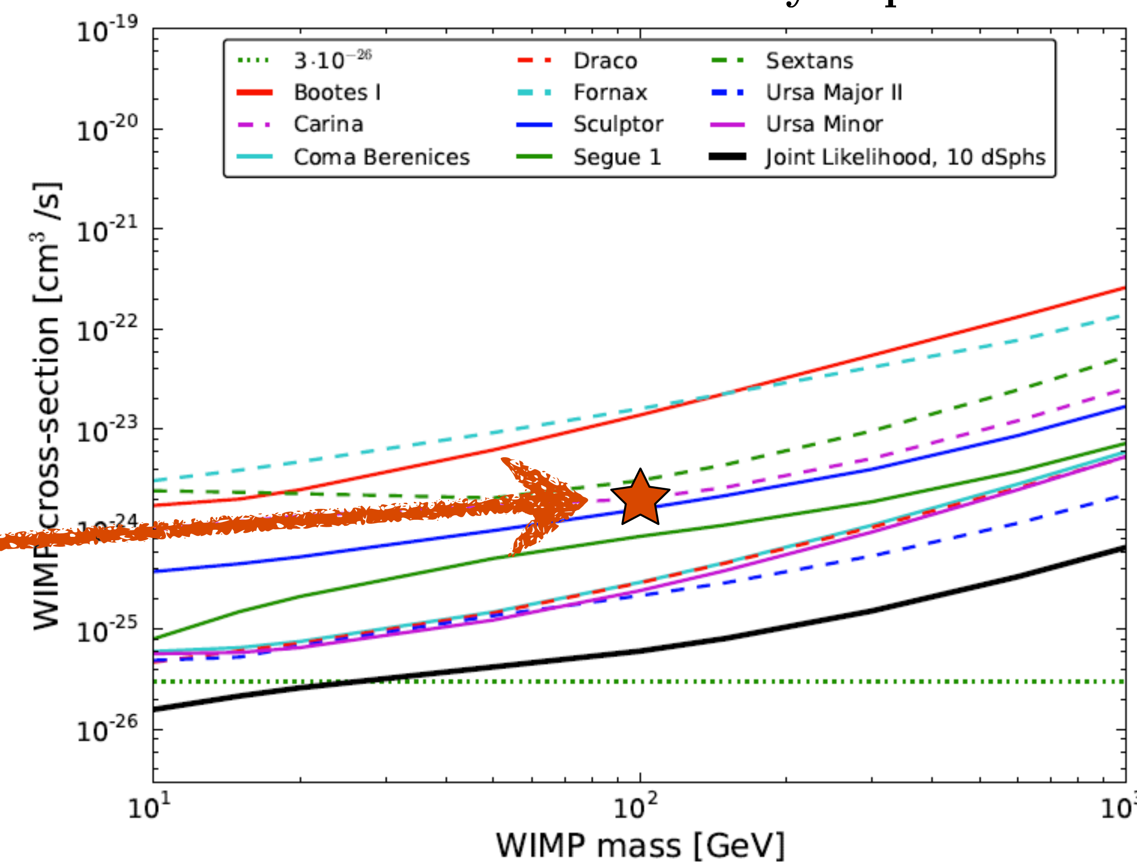
Prob(Don't Detect Simulated Satellite j)

$$\boxed{P_i(\langle\sigma v\rangle)} = \prod_j \boxed{(1-\epsilon_{i,j}(\langle\sigma v\rangle))}$$

Prob(Don't Detect Any Satellites in Simulation)

$$\langle\sigma v\rangle \sim \mathbf{2 \times 10^{-24}\ cm^3\ s^{-1}}$$

Two-Year Dwarf Galaxy Paper



- **What would an interesting signal look like?**
  - **Multiple unassociated sources sharing a common hard spectral feature**
  - **Optical follow up of an unusual unassociated source reveals a new ultra-faint dwarf.**

Search for Unassociated Satellites

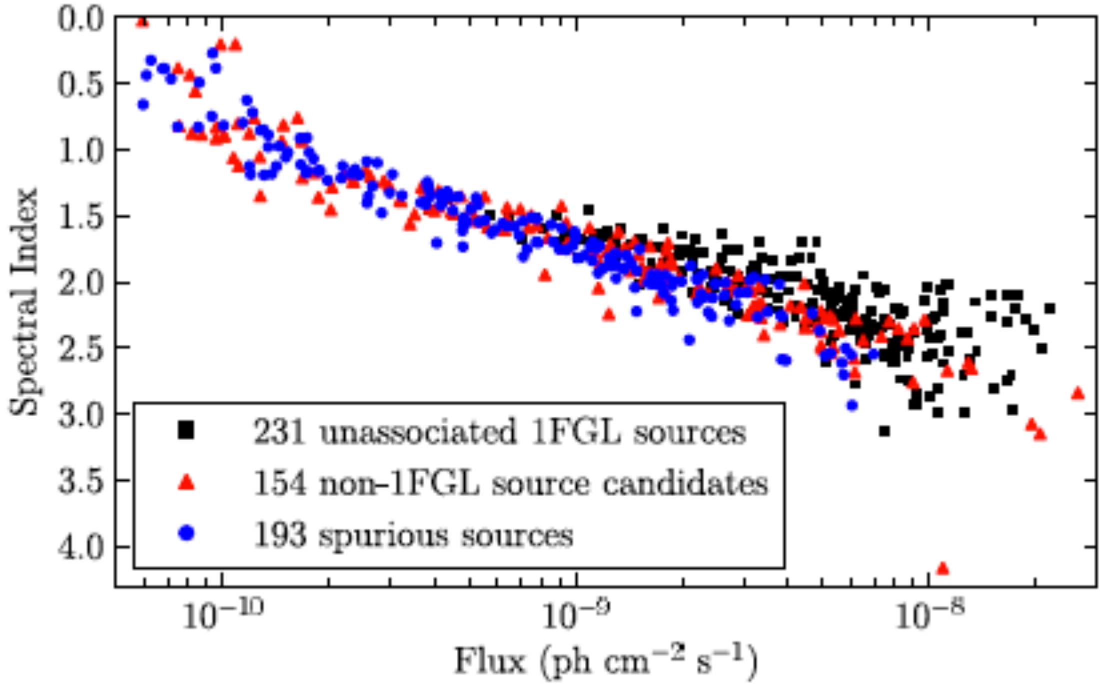


Figure 5. Distribution of spectral indices and integral fluxes from 200 MeV to 300 GeV for the 385 high-latitude unassociated sources and source candidates. The squares are the 231 unassociated sources from the 1FGL catalog, while the triangles are the 154 additional source candidates detected with `Sourcelike`. The circles are the 193 spurious sources found in a Monte Carlo simulation of background only.

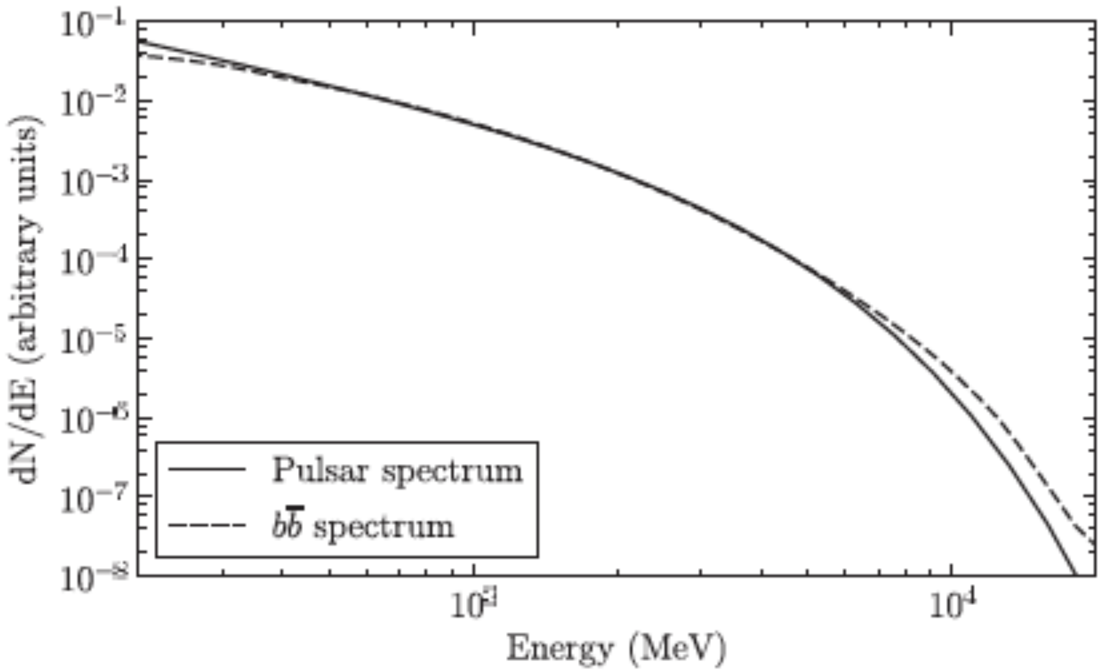


Figure 3. Best-fit exponentially cutoff power law (with $\Gamma = 1.22$ and $E_{\rm cut} = 1.8$ GeV) of the millisecond pulsar 1FGL J0030+0451 (solid line) and the best-fit $b\bar{b}$ spectrum (with $M_{\rm WIMP} = 25$ GeV) of this pulsar (dashed line).

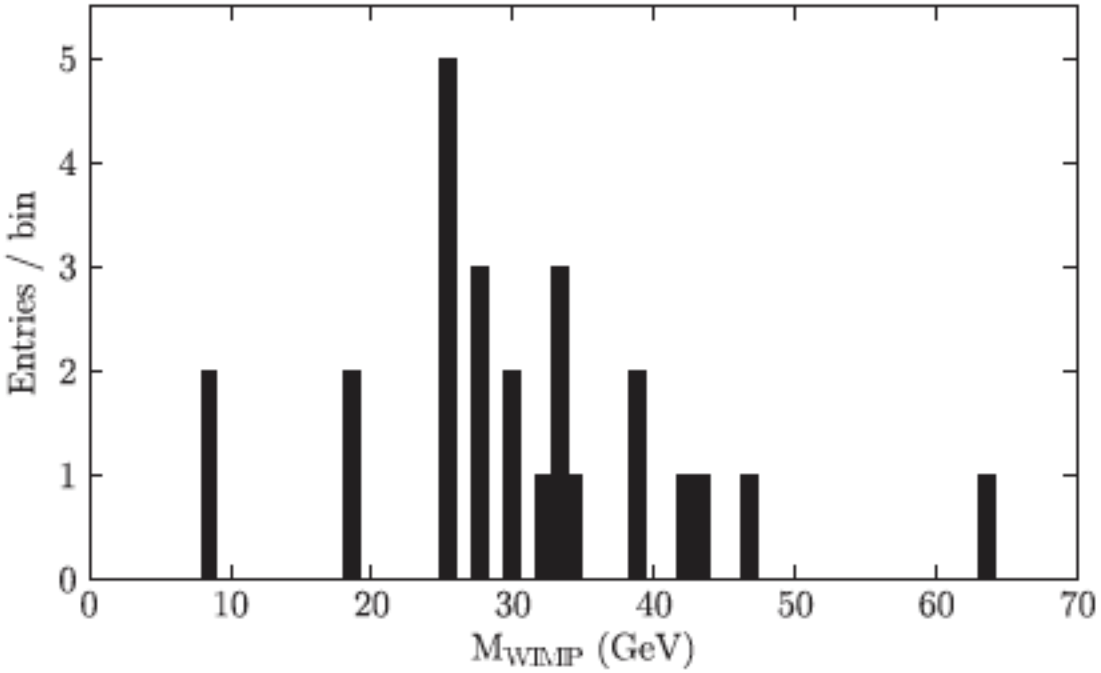
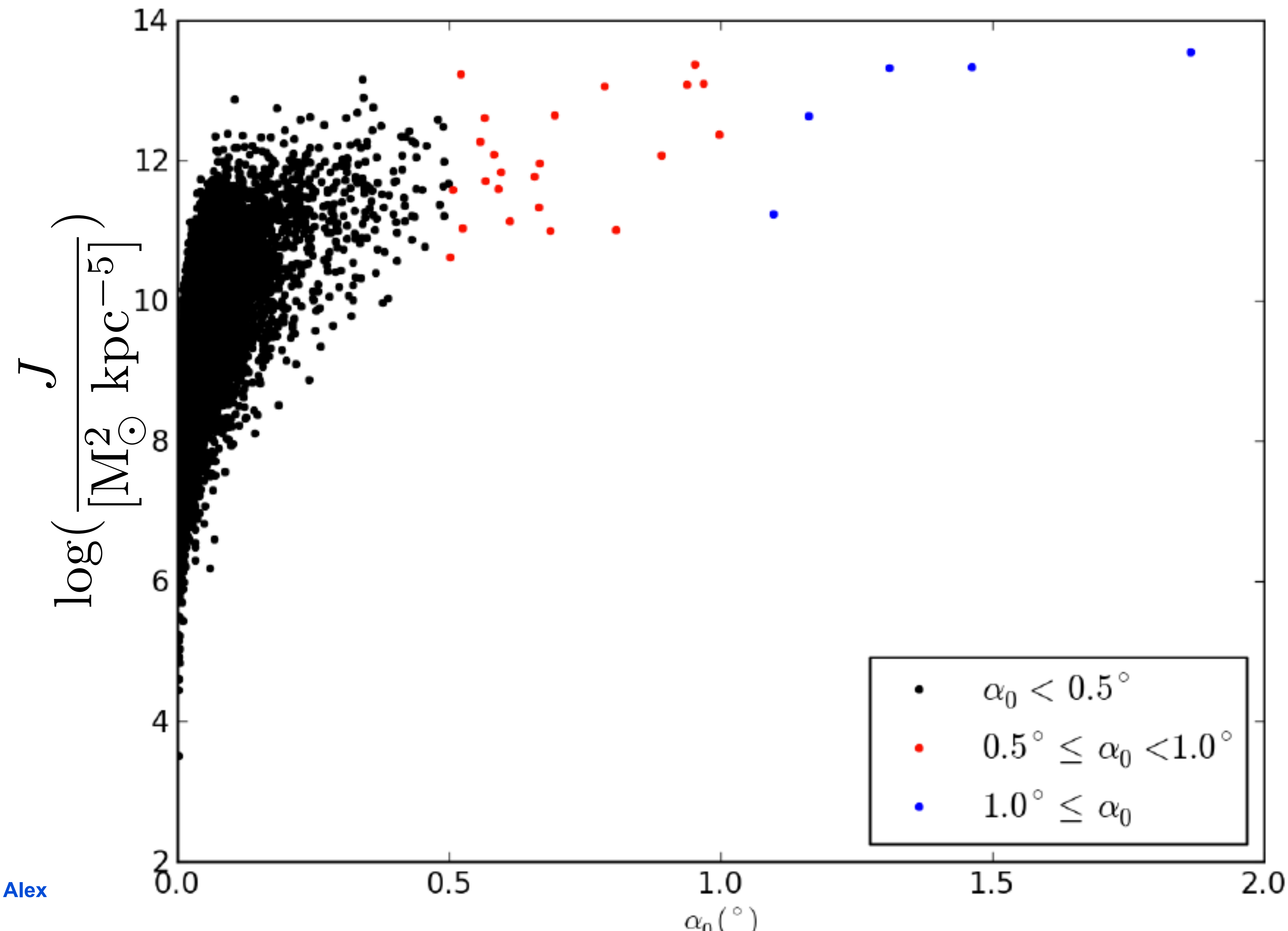


Figure 4. Best-fit dark matter mass ($M_{\rm WIMP}$) coming from fitting 25 high-latitude ($|b| > 20°$) pulsars with a $b\bar{b}$ annihilation spectrum.

Subhalo Spatial Extension

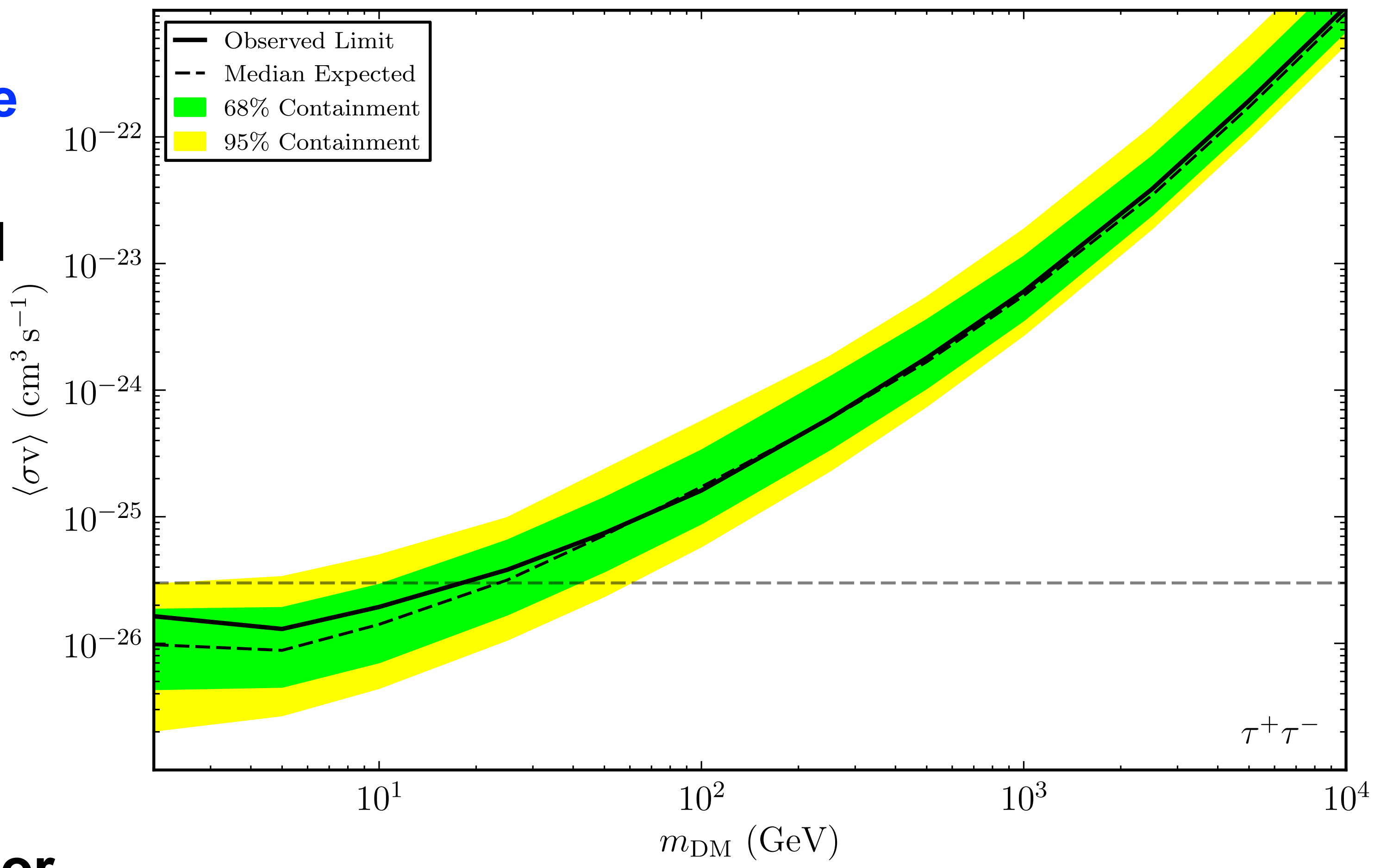


Back-up Slides:
Dwarf Analysis

Contributions to Combined Analysis

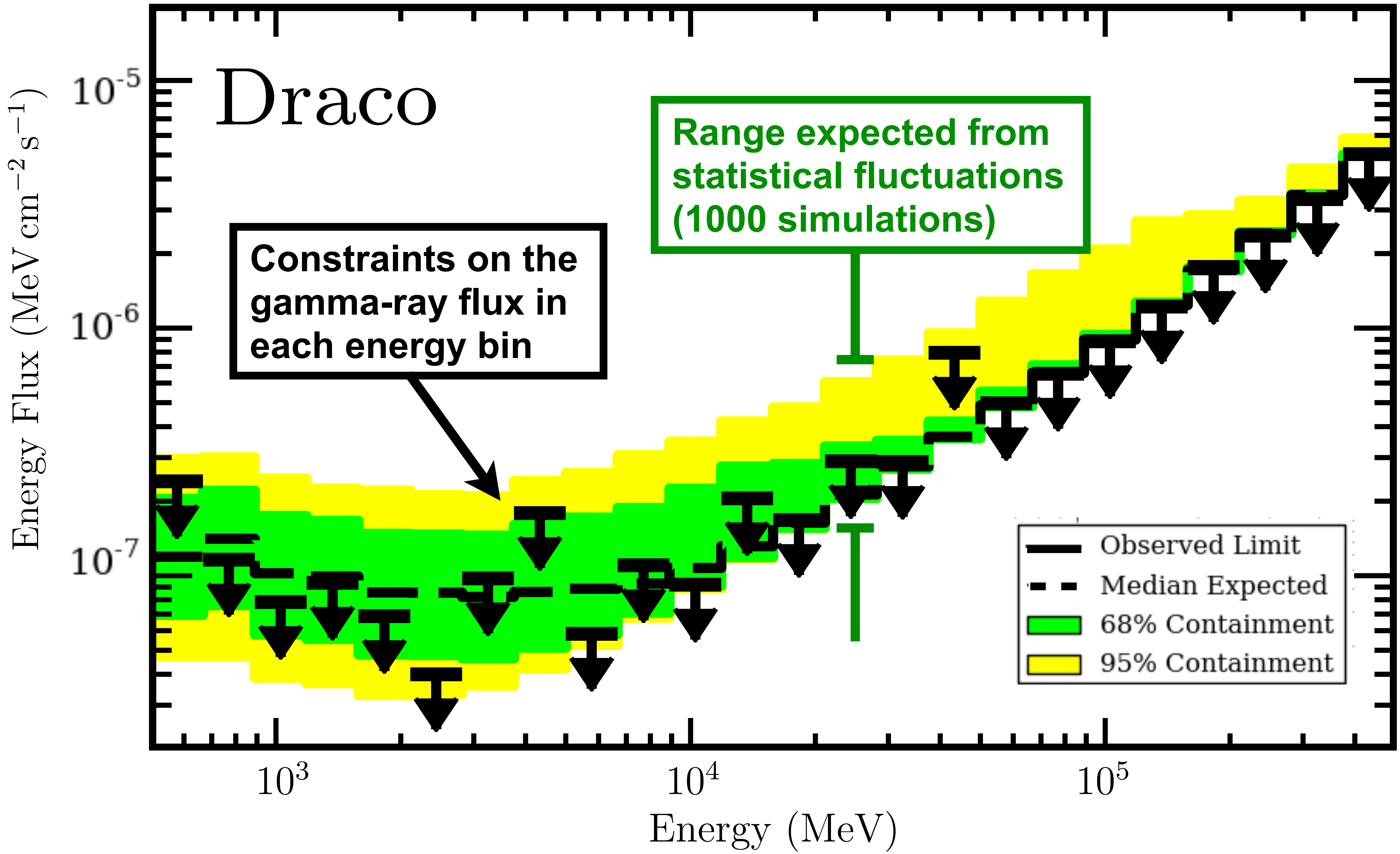
- If this is a signal, the gamma-ray flux should be correlated with the dark matter content.
- Sensitivity of the combined analysis dominated by dwarfs with the largest J-factors: Coma Berenices, Draco, Segue 1, Ursa Major II, Ursa Minor, Willman 1
- Largest gamma-ray excesses associated with ultra-faint dwarfs: Segue 1, Ursa Major II, Willman 1
- However, comparable excesses associated with low J-factor dwarfs: Hercules, Sculptor, Canes Venatici II
- Additionally, no excess coincident with large J-factor dwarfs: Coma Berenices, Draco, Ursa Minor
- No significant correlation between J-factor and gamma-ray signal strength
- Removing ultra-faint dwarfs changes limit by 20% at low mass and 2x at high mass

Remove Segue 1, Ursa Major II, and Willman 1



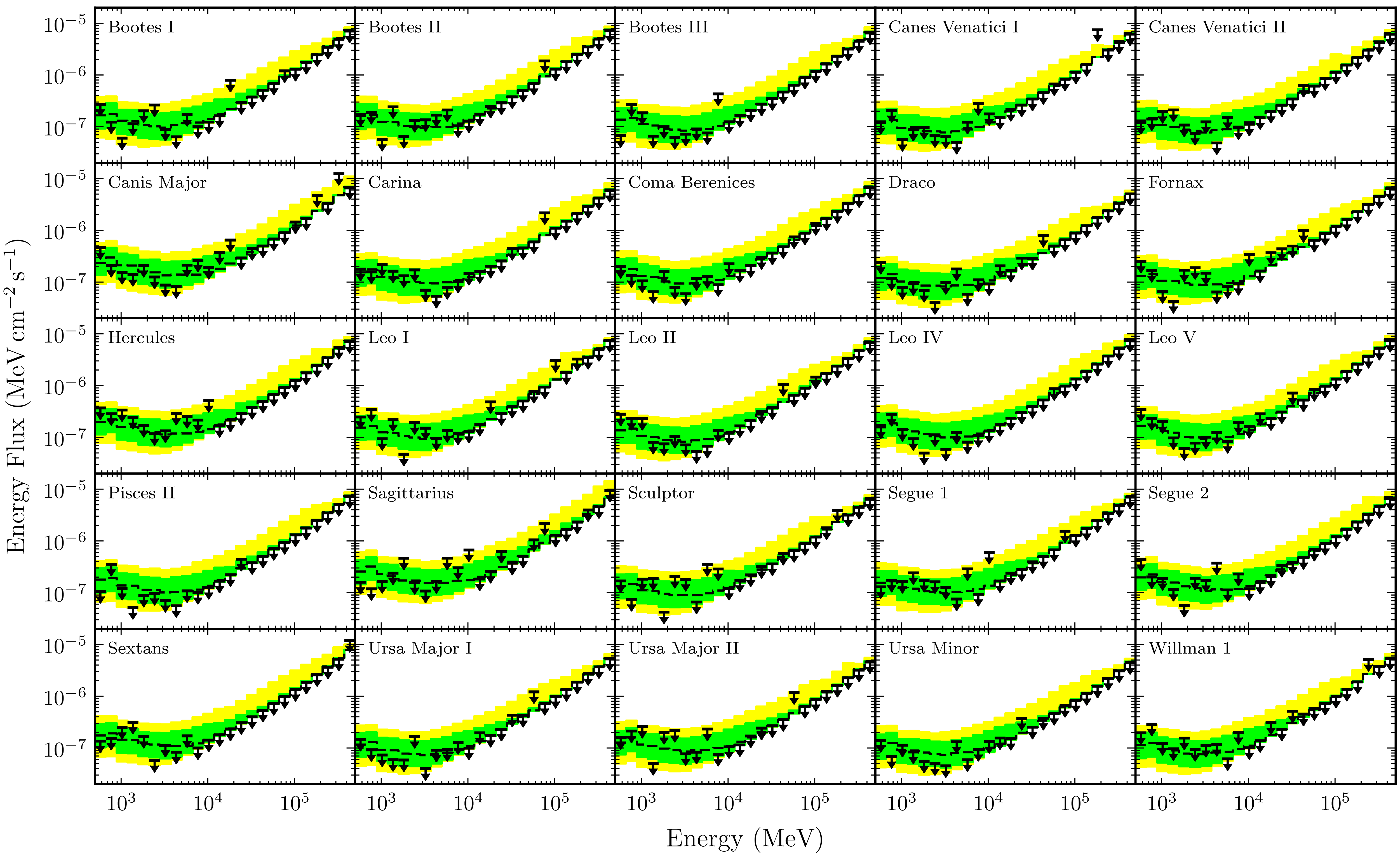
Ackermann et al. PRD 89 042001 (2014)

Differential Sensitivity



Ackermann et al. PRD 89 042001 (2014)

Individual Dwarf Galaxies



Ackermann et al. PRD 89 042001 (2014)

- **Dwarf dark matter content estimated from the line-of-sight velocities of member stars (e.g. Martinez et al. 2009)**

- **Mass within half-light radius of each dwarf is largely independent of assumptions on the cored or cuspy nature of the inner profile**

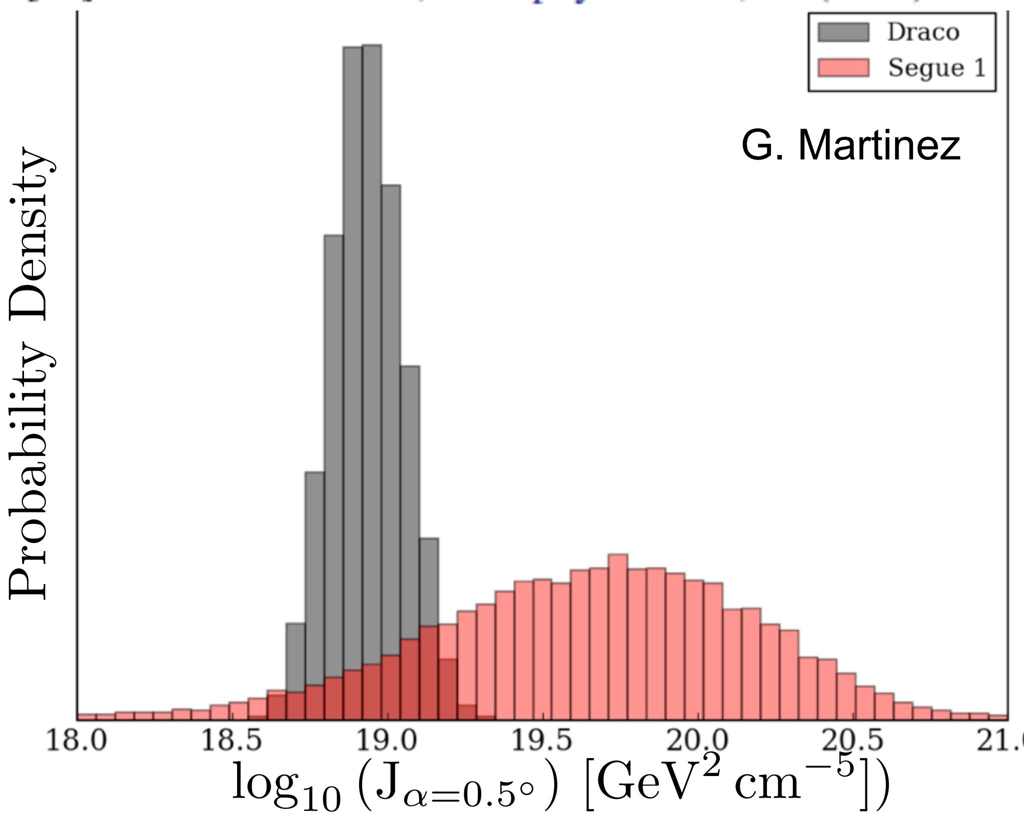
- **Calculate the total integrated J-factor within a cone with angular radius of 0.5 degrees (~ comparable to dwarf half-light radius)**

- **The posterior distribution and likelihood function for J are well described by a log-normal function**

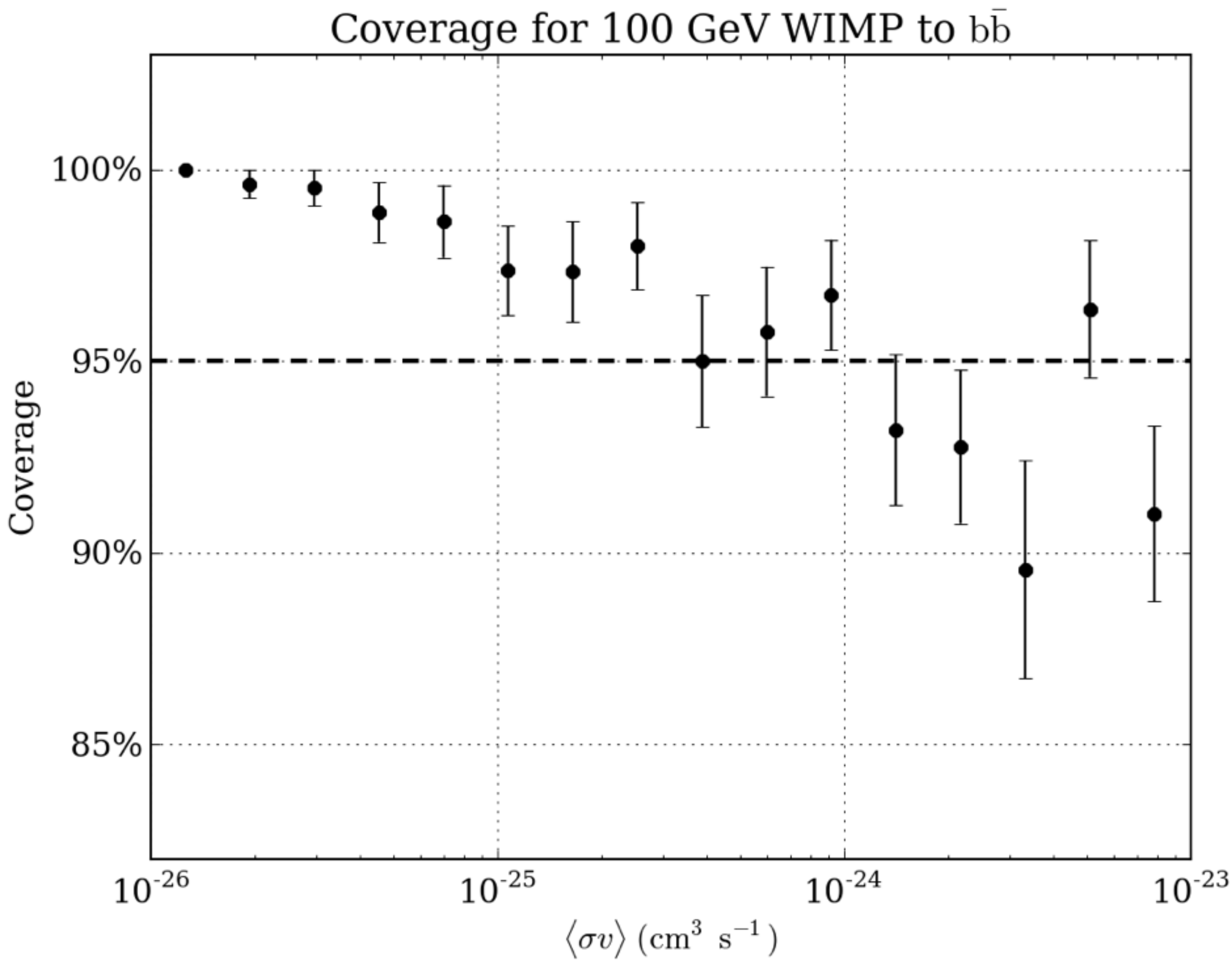
- **Some new ultra-faint dwarfs have the largest J-factors and the largest uncertainties**

Name	l (degree)	b (degree)	d (kpc)	$\overline{\log_{10}(J)}$ ($\log_{10}[\mathrm{GeV}^2\ \mathrm{cm}^{-5}]$)	σ	Reference
Bootes I	358.08	69.62	60	17.7	0.34	[1]
Carina	260.11	−22.22	101	18.0	0.13	[2]
Coma Berenices	241.9	83.6	44	19.0	0.37	[3]
Draco	86.37	34.72	80	18.8	0.13	[2]
Fornax	237.1	−65.7	138	17.7	0.23	[2]
Sculptor	287.15	−83.16	80	18.4	0.13	[2]
Segue 1	220.48	50.42	23	19.6	0.53	[4]
Sextans	243.4	42.2	86	17.8	0.23	[2]
Ursa Major II	152.46	37.44	32	19.6	0.40	[3]
Ursa Minor	104.95	44.80	66	18.5	0.18	[2]

[1] S.E. Koposov *et al.*, Astrophys. J. **736**, 146 (2011).
[2] M.G. Walker *et al.*, Astrophys. J. **704**, 1274 (2009).
[3] J.D. Simon and M. Geha, Astrophys. J. **670**, 313 (2007).
[4] J.D. Simon *et al.*, Astrophys. J. **733**, 46 (2011).



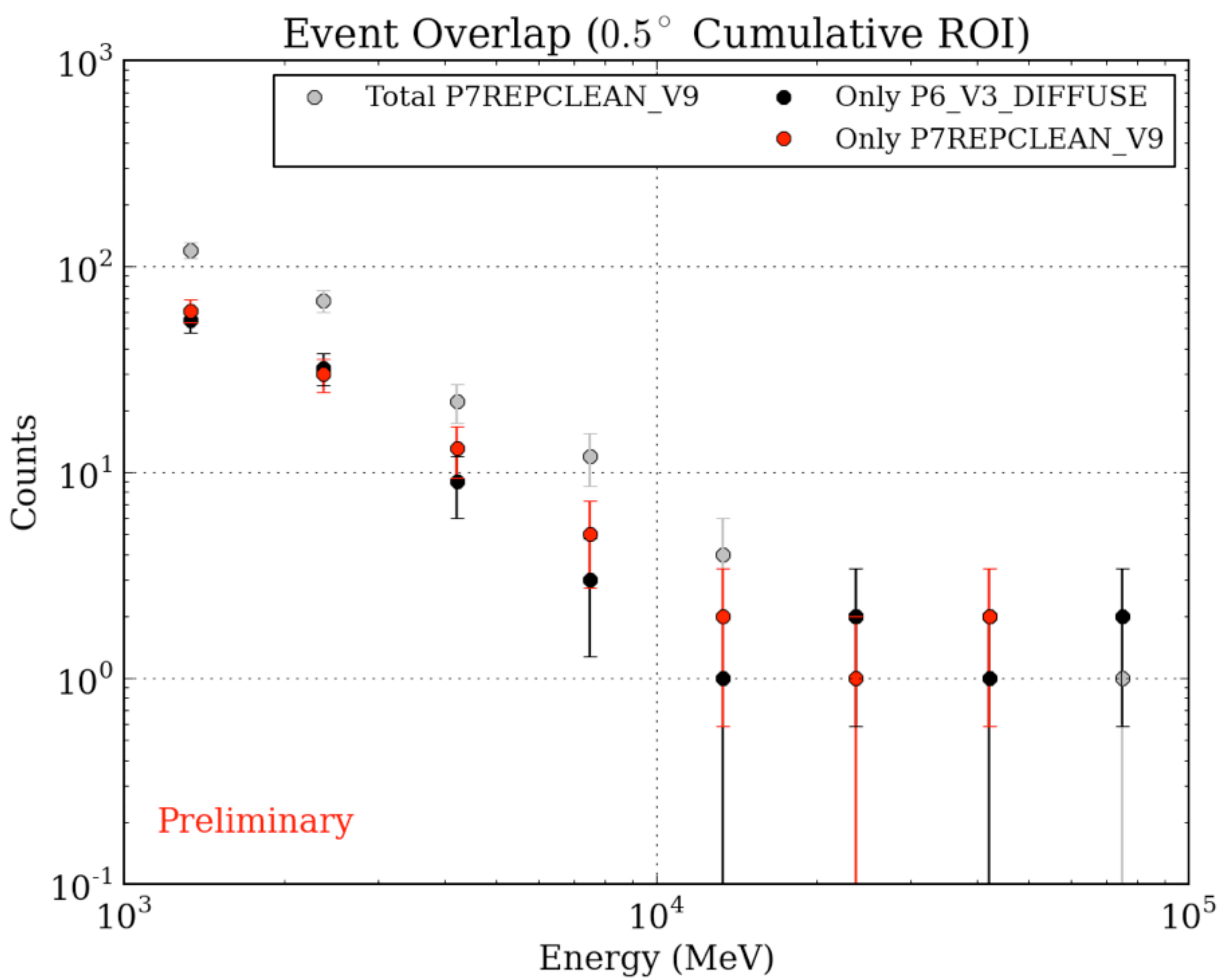
Coverage


Coverage for 100 GeV WIMP to $b\bar{b}$
Coverage
100%
95%
90%
85%
10^{-26}
10^{-25}
10^{-24}
10^{-23}
$\langle\sigma v\rangle$ ($\mathrm{cm^3\ s^{-1}}$)

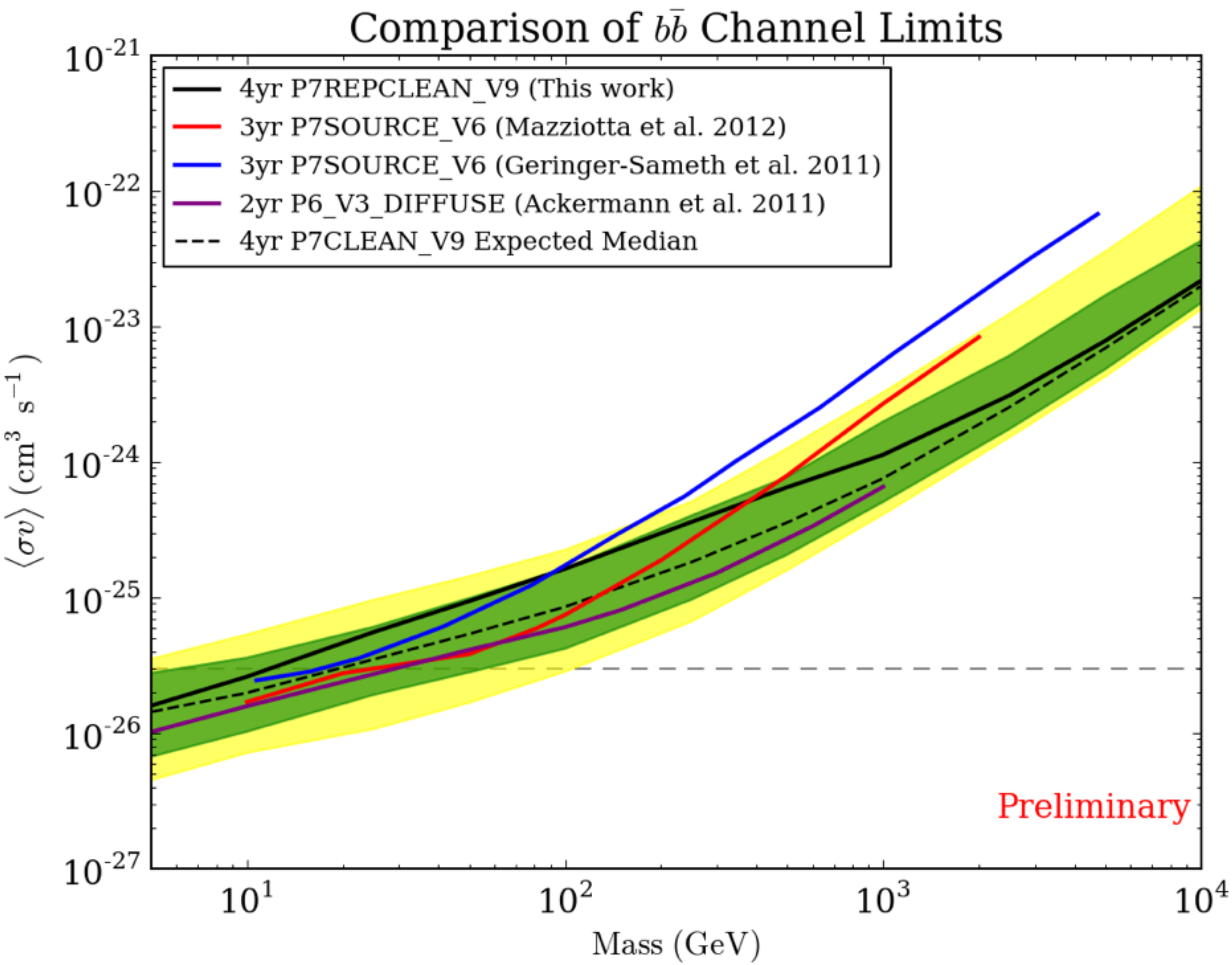
Statistical Fluctuations

- **The P6_V3_DIFFUSE and P7REPCLEAN_V9 differ on an event-by-event basis**
  - **Only ~70% of events above 1 GeV shared by the two event classes**
  - **Only ~50% of events above 10 GeV and within 0.5 deg. of the dwarfs are shared by the event classes**

- **What accounts for this difference?**
  - **Pass 7 does a better job of mitigating instrumental pile-up**
  - **Required retraining of multivariate classification**
  - **Results in a statistical re-shuffling of events**



Comparison



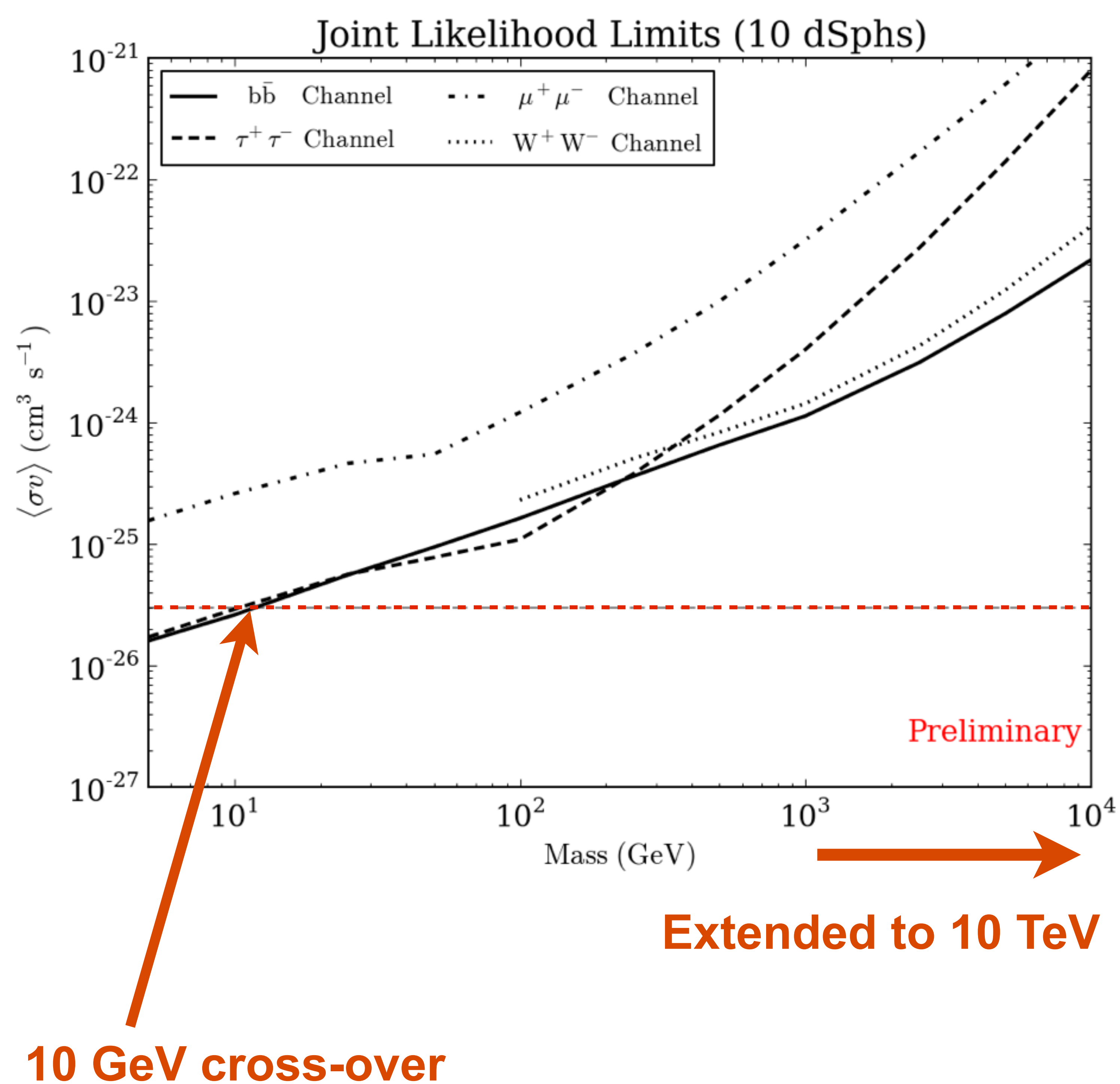
Comparison of $b\bar{b}$ Channel Limits
4yr P7REPCLEAN_V9 (This work)
3yr P7SOURCE_V6 (Mazziotta et al. 2012)
3yr P7SOURCE_V6 (Geringer-Sameth et al. 2011)
2yr P6_V3_DIFFUSE (Ackermann et al. 2011)
4yr P7CLEAN_V9 Expected Median
Preliminary
$\langle \sigma v \rangle$ (cm^3 s^{-1})
Mass (GeV)
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^1
10^2
10^3
10^4

4-Year Pass 7 Analysis

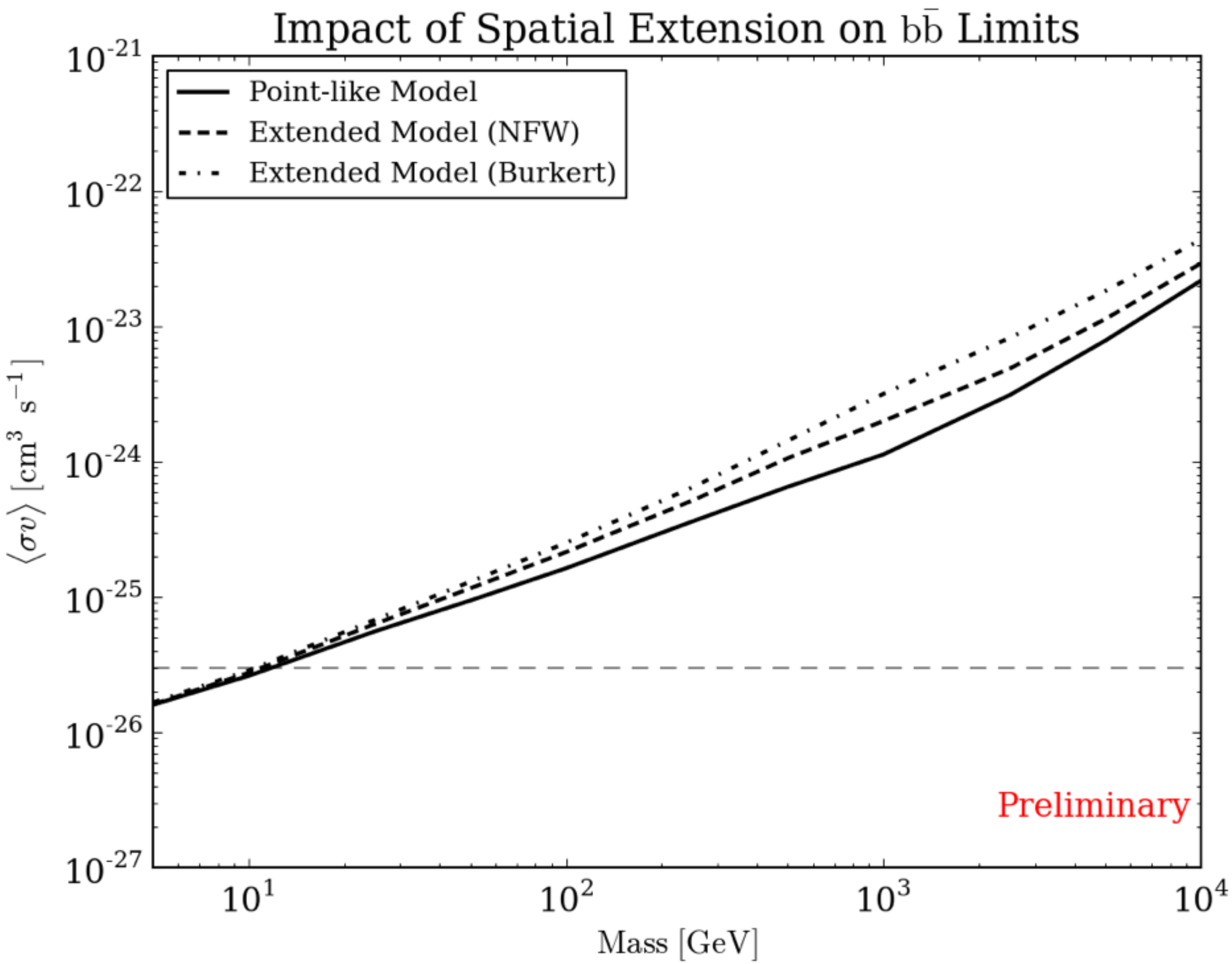
- **Joint likelihood analysis of:**
  - **Extended time period:**
    4 years
  - **Improved instrument response:**
    P7REPCLEAN_V9
  - **Expanded photon energy range:**
    100 MeV - 500 GeV
  - **Constrain higher WIMP masses:**
    5 GeV - 10 TeV
  - **Same 10 dwarf galaxies**

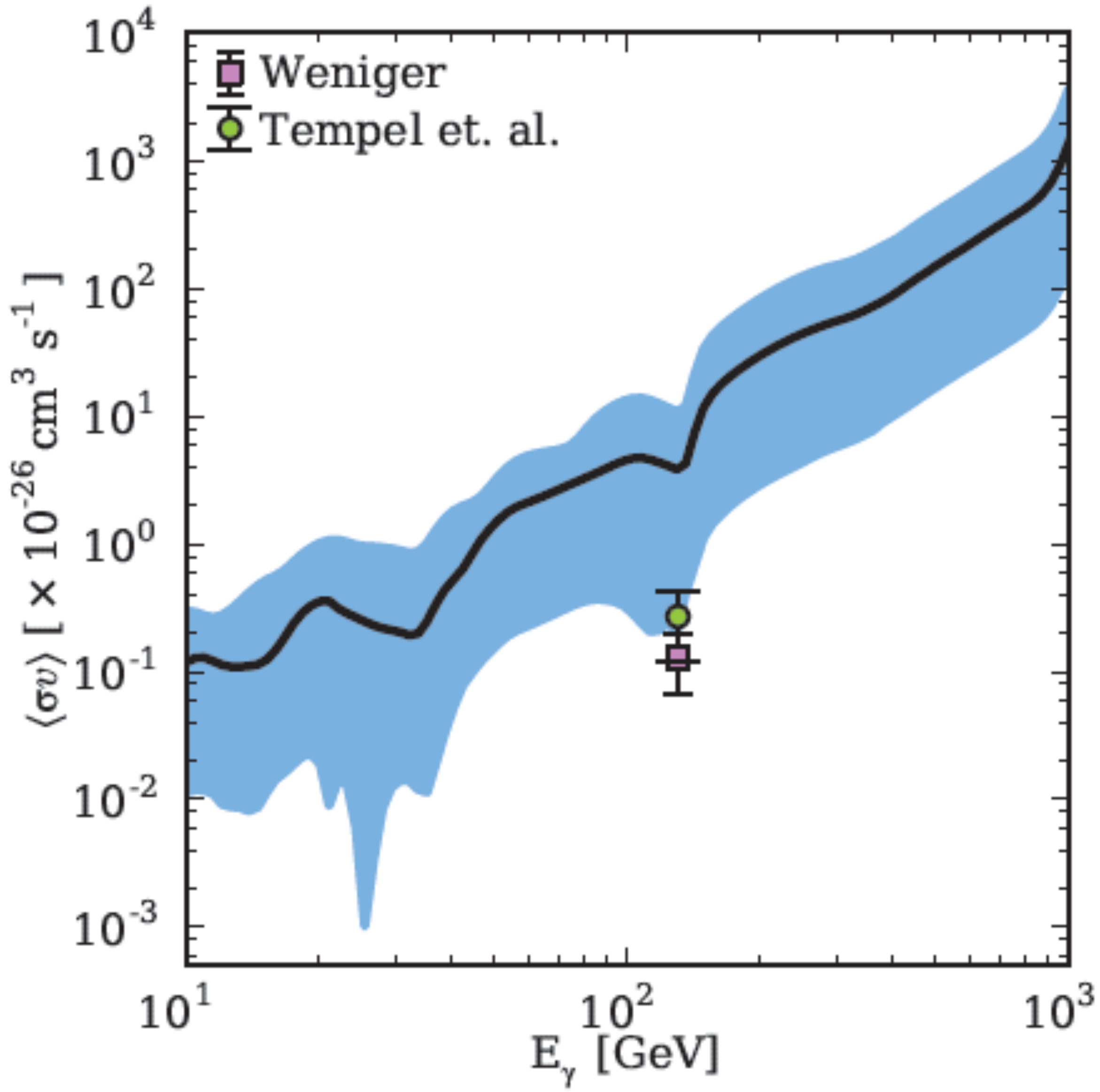
- **Model astrophysical backgrounds based on 2 years of Pass 7 data**
  - **2FGL catalog sources (normalization free within 5˚)**
  - **2-year diffuse background models (normalization free)**

- **Include statistical uncertainties in the solid-angle-integrated J-factor**



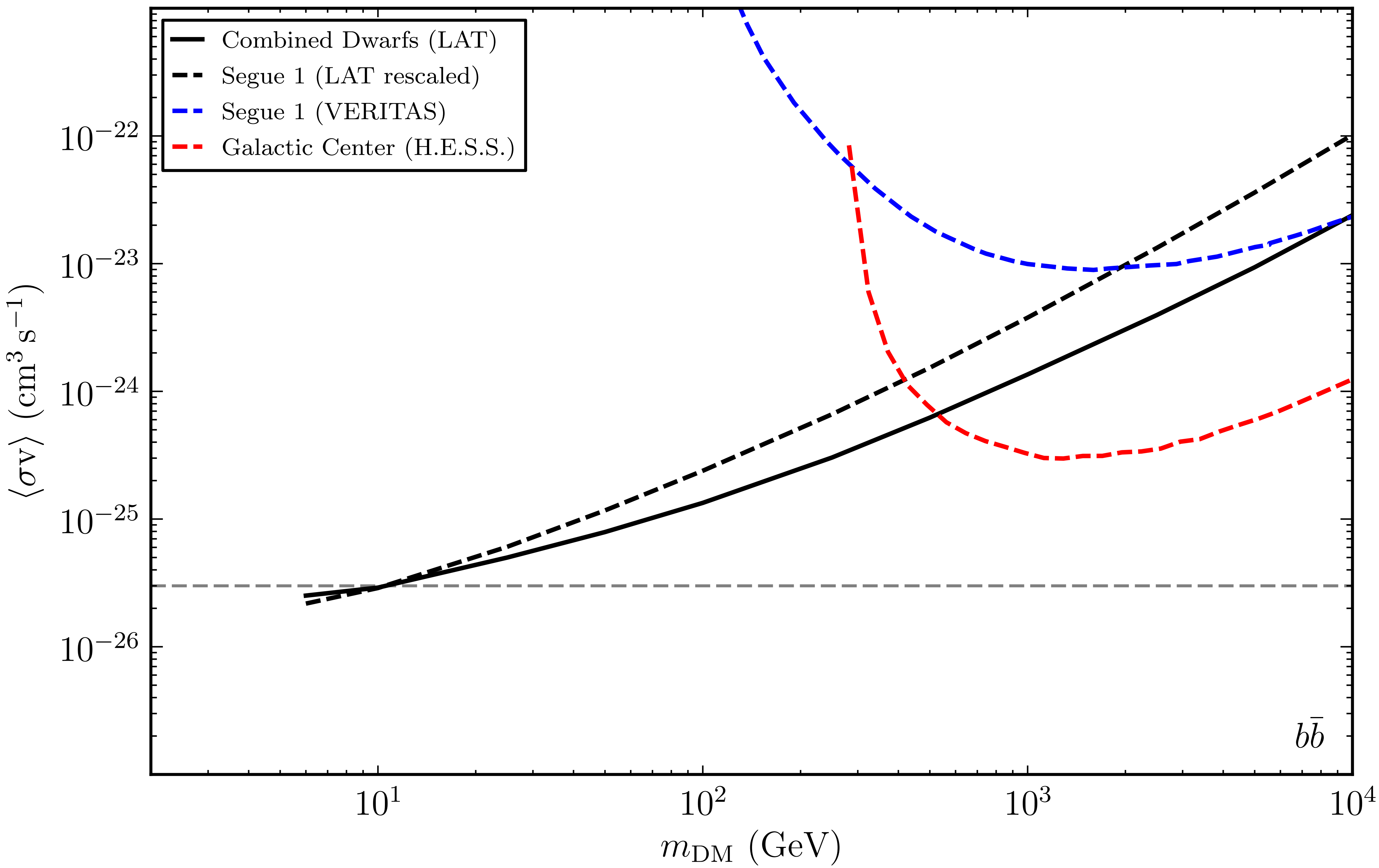
Spatial Extension





Geringer-Sameth & Koushiappas (2012)

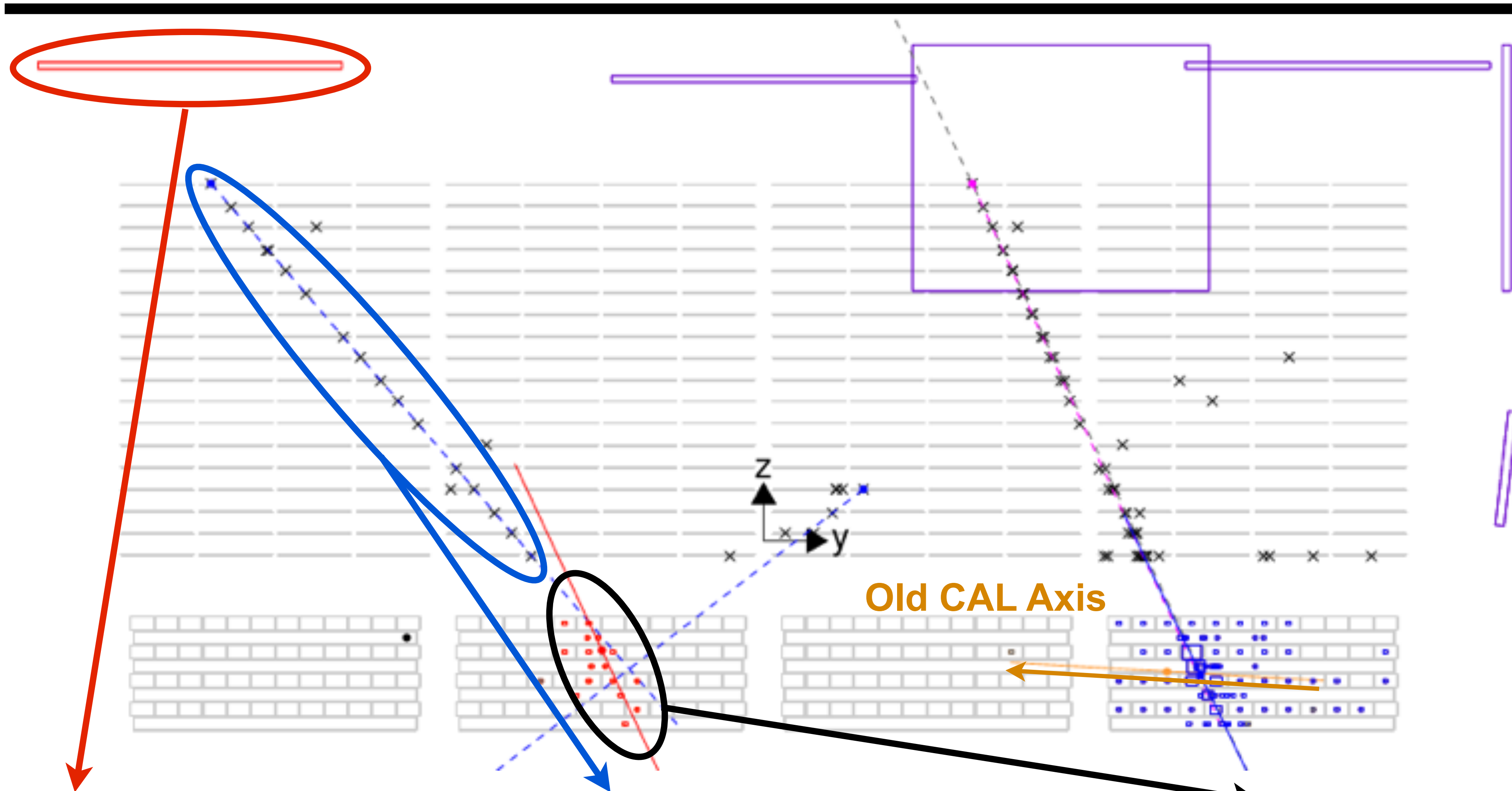
Comparison with ACTs



Ackermann et al. PRD 89 042001 (2014)

Back-up Slides:
Future

Pass 8: Ghost Busting



ACD Ghost Hit

- Identify ACD tiles with ghost energy deposits using the fast ACD veto information.
- Can this be accomplished without sacrificing background rejection power?
- Needs more study

TKR Ghost Hits

- Identify ghost energy in the TKR from TOT information and out-of-time hits.
- Remove tagged hits before running track finding.
- Could search for in-time hits on ghost tracks.

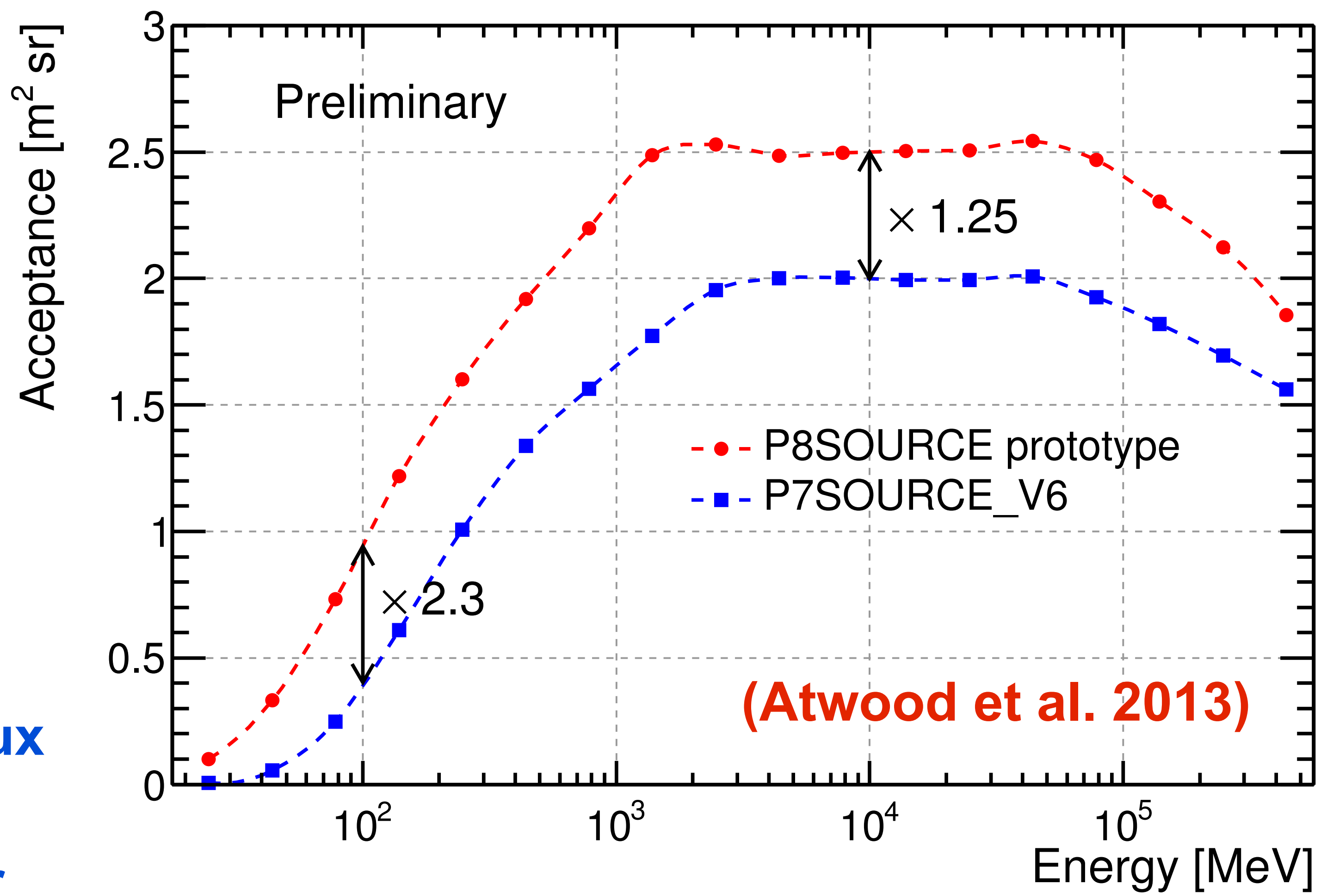
CAL Ghost Cluster

- Identify through CAL clustering and cluster classification.
- Work only with gamma cluster (effectively removing ghost) or remove ghost cluster and combine remaining crystals.

Ghost removal goes hand-in-hand with background rejection!

Pass8: Improved LAT Performance

- **Improvements to the LAT instrument performance:**
  - **Increased energy range**
  - **Increased effective area**
  - **Improved angular resolution**
  - **Better background rejection**
  - **New event classes**

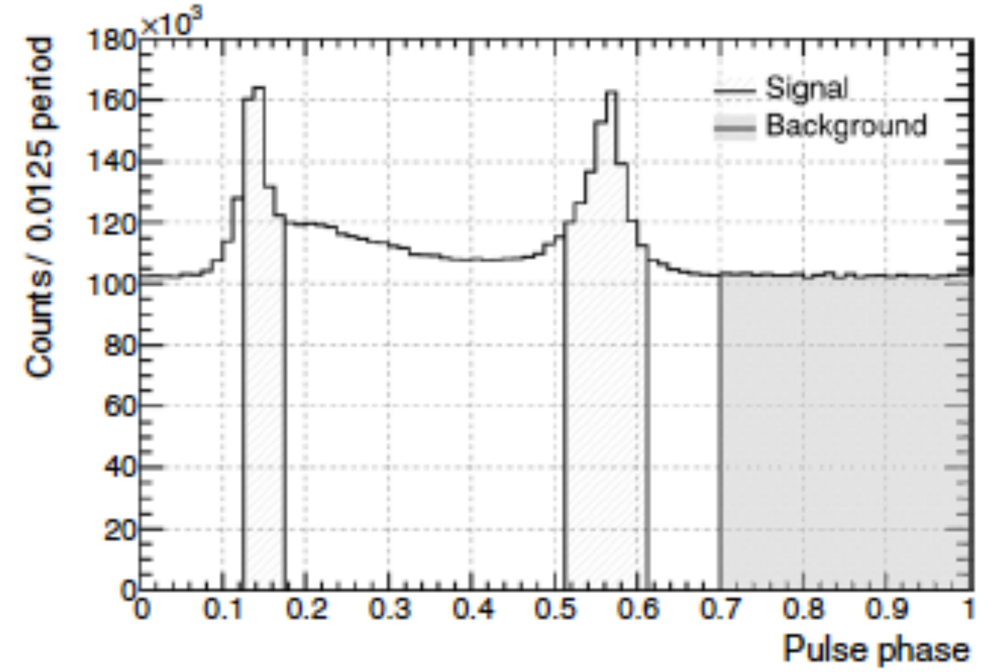


5 Decades in Energy (3 TeV)

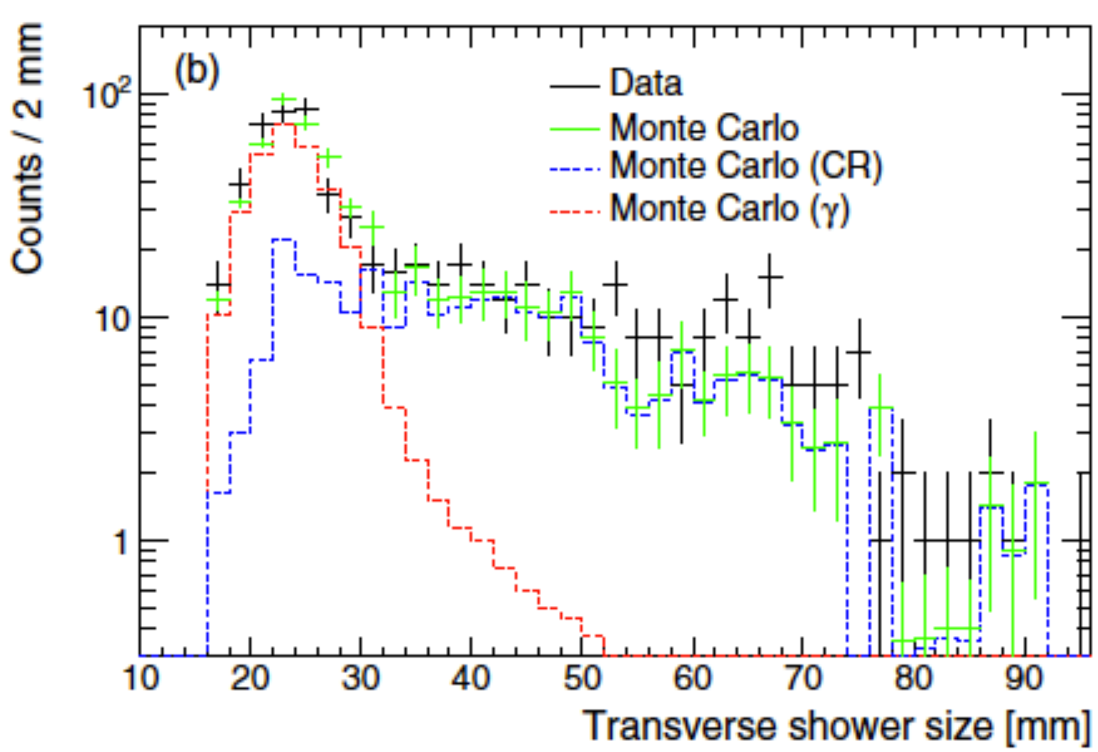
- **Impacts for dark matter:**
  - **Energy Range <==> explore new high-mass parameter space**
  - **Effective Area <==> increased flux sensitivity**
  - **Angular Resolution <==> greater sensitivity to spatially extended sources**
  - **New Event Classes <==> check systematic effects in event selection**

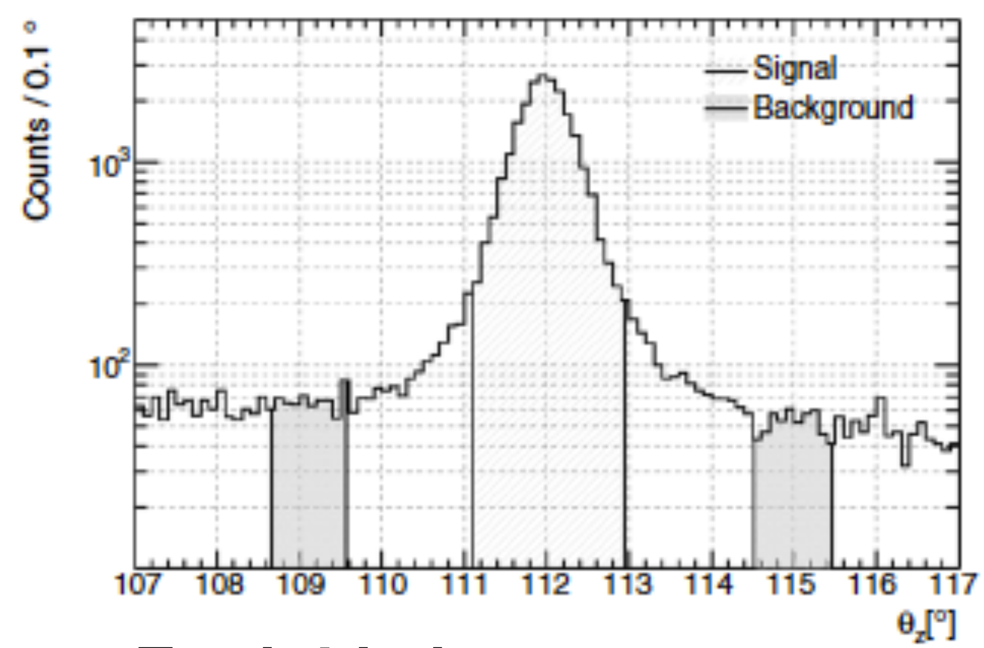
Improving the LAT Instrument

- **Event reconstruction and classification algorithms were developed pre-launch on Monte Carlo**
- **Validate the accuracy of the Monte Carlo against flight data**
- **Incorporate effects from the orbital environment**
- **Identify areas in the reconstruction where large benefits are possible**



Vela Pulsar





Earth Limb

Residual Background Contamination

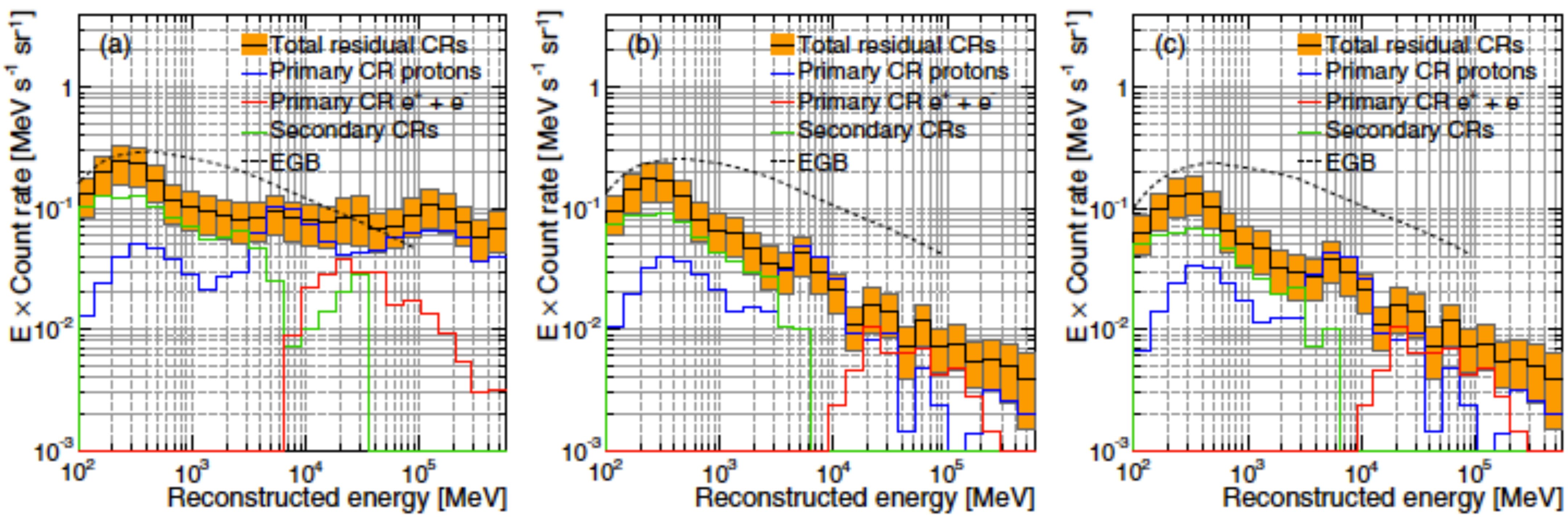
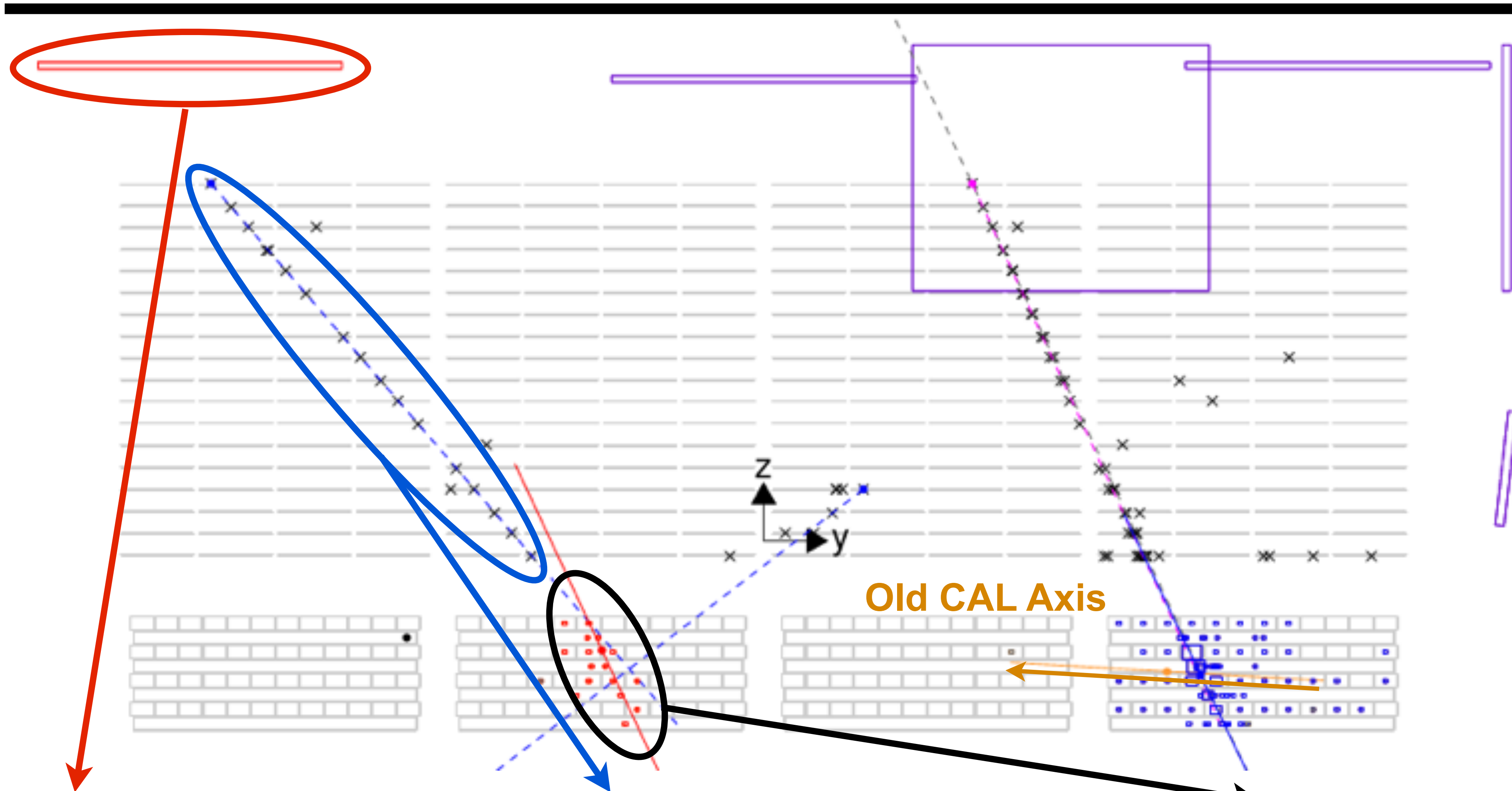


Figure 28. Best estimates of differential rates of residual particle backgrounds for the P7SOURCE (a), P7CLEAN (b), and P7ULTRACLEAN (c) event classes. Individual contributions from primary CR protons, primary CR electrons, and the secondaries from CR interactions are shown; the corresponding count rates for the extragalactic γ-ray background measured by *Fermi* (Abdo et al. 2010e) are also overlaid for comparison.

Ghost Removal



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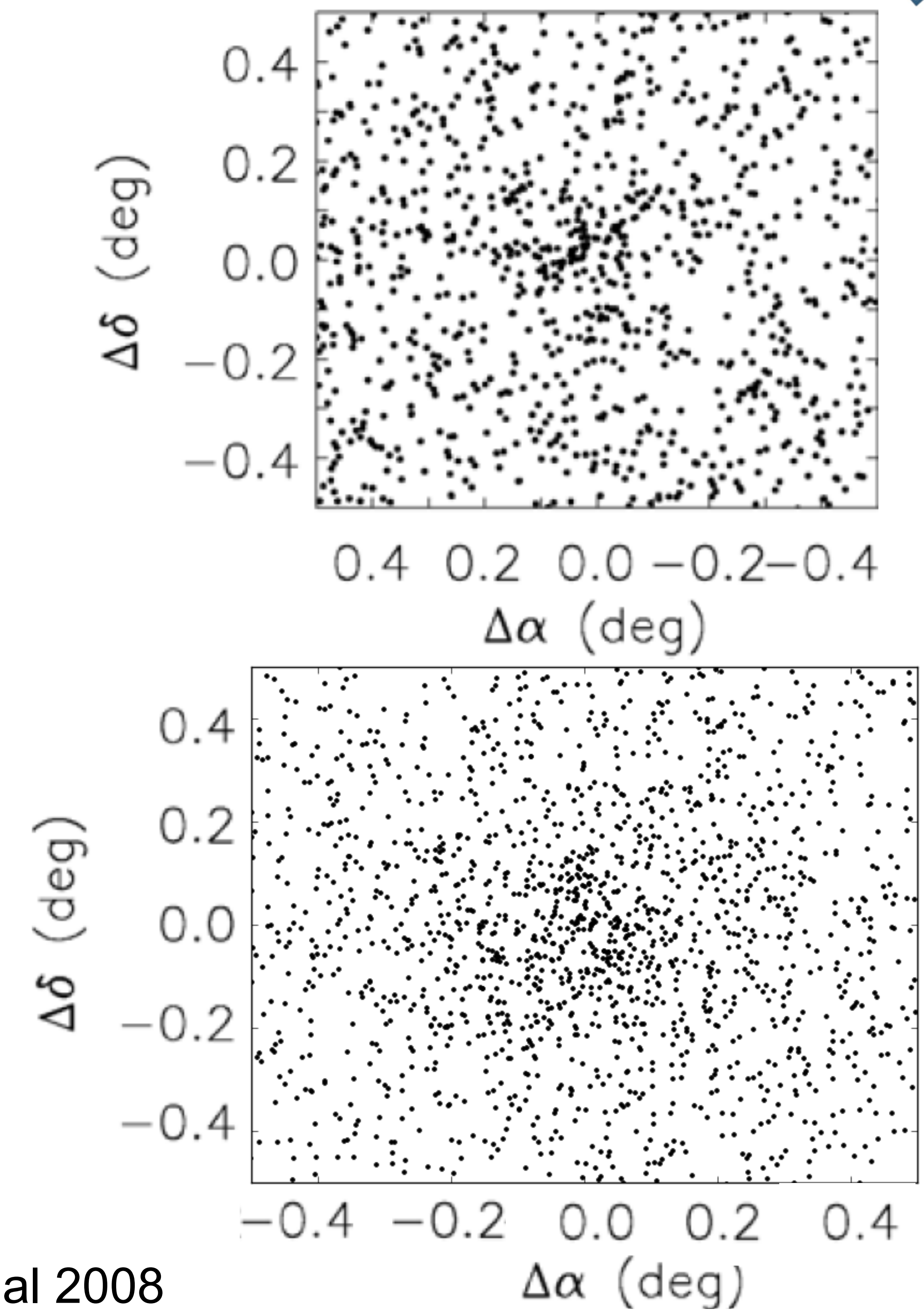
CAL Ghost Cluster

- Identify through CAL clustering and cluster classification.
- Work only with gamma cluster (effectively removing ghost) or remove ghost cluster and combine remaining crystals.

Ghost removal goes hand-in-hand with background rejection!

Finding Satellite Galaxies

- **Finding satellite galaxies has much in common with finding weak gamma-ray sources**
  - **Looking for spatial over-densities among a structured diffuse background**
  - **Contamination from mis-classified "objects" (cosmic-rays / galaxies)**
  - **Simultaneously fitting in spatial and energy / color dimension**
  - **N_stars (full survey) ~ 1e8**
    N_photons (10 yrs) ~ 1.5e8

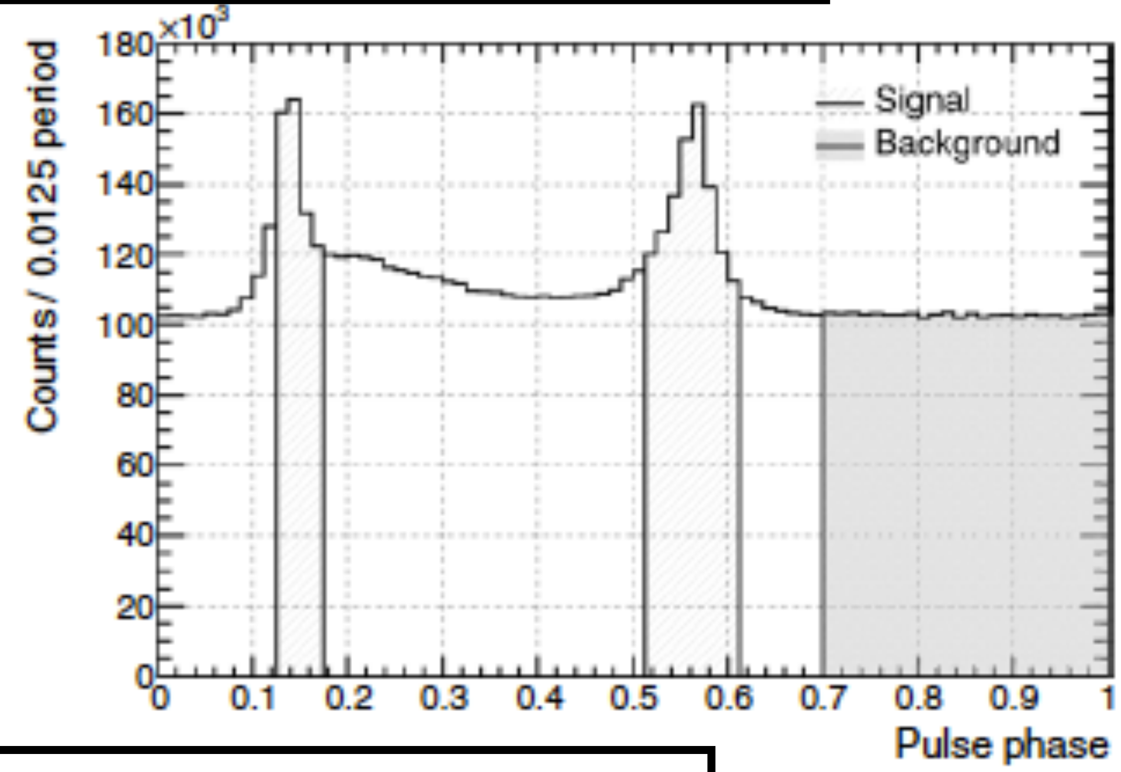


Walsh et al 2008

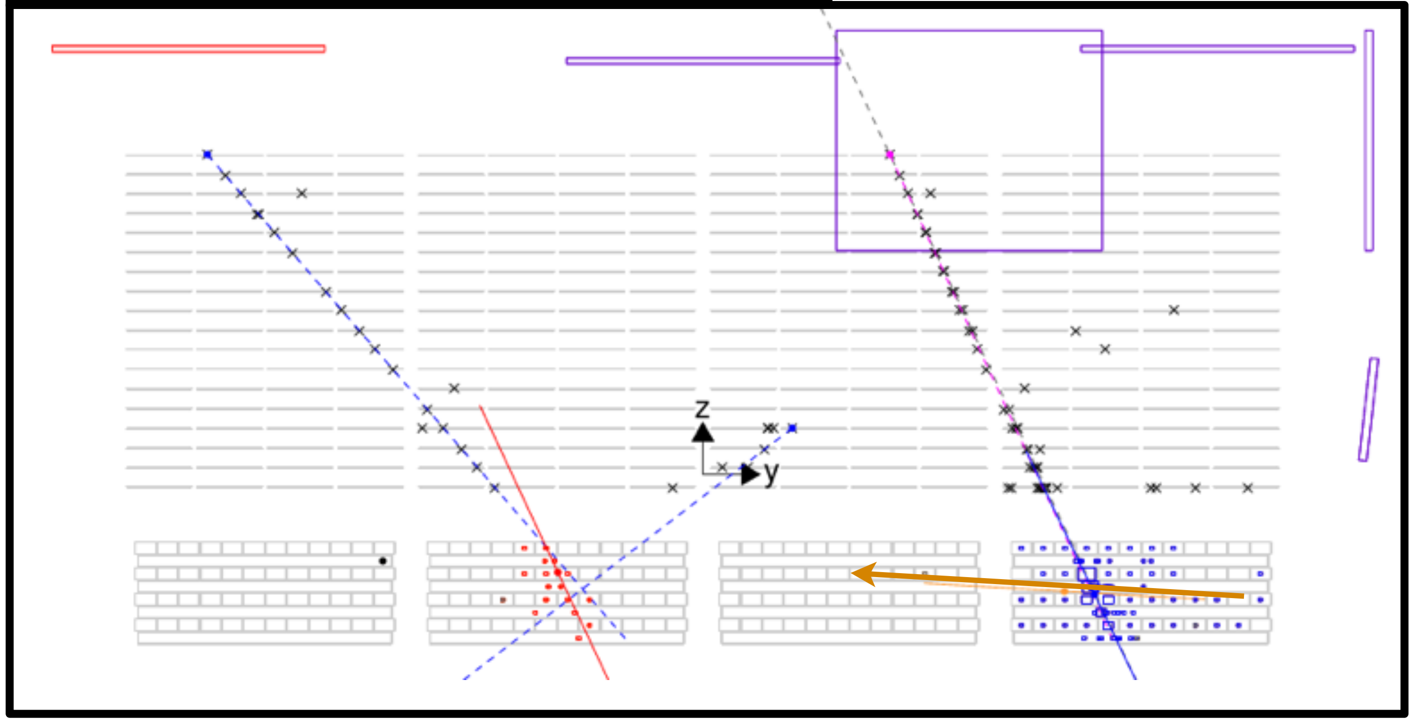
Improvements to the Fermi-LAT

- While the LAT hardware cannot be altered, an enormous amount of information is recorded for each event
- Allows for major improvements to reconstruction and background rejection software
- Until now, the development of this software was completely Monte Carlo driven (with some minor tweaks to mitigate environment effects)
- We now have the opportunity to optimize it for the true LAT operating conditions and science interests
  - Flight data validation of Monte Carlo
  - Experience with the orbital environment
  - Direction from science groups

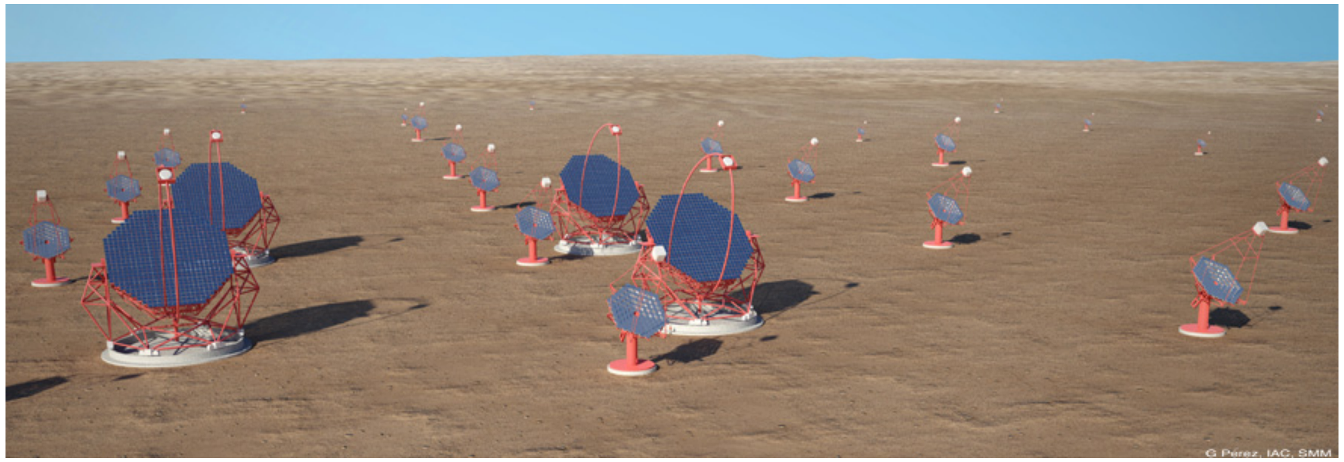
Pulsars as Validation Sample



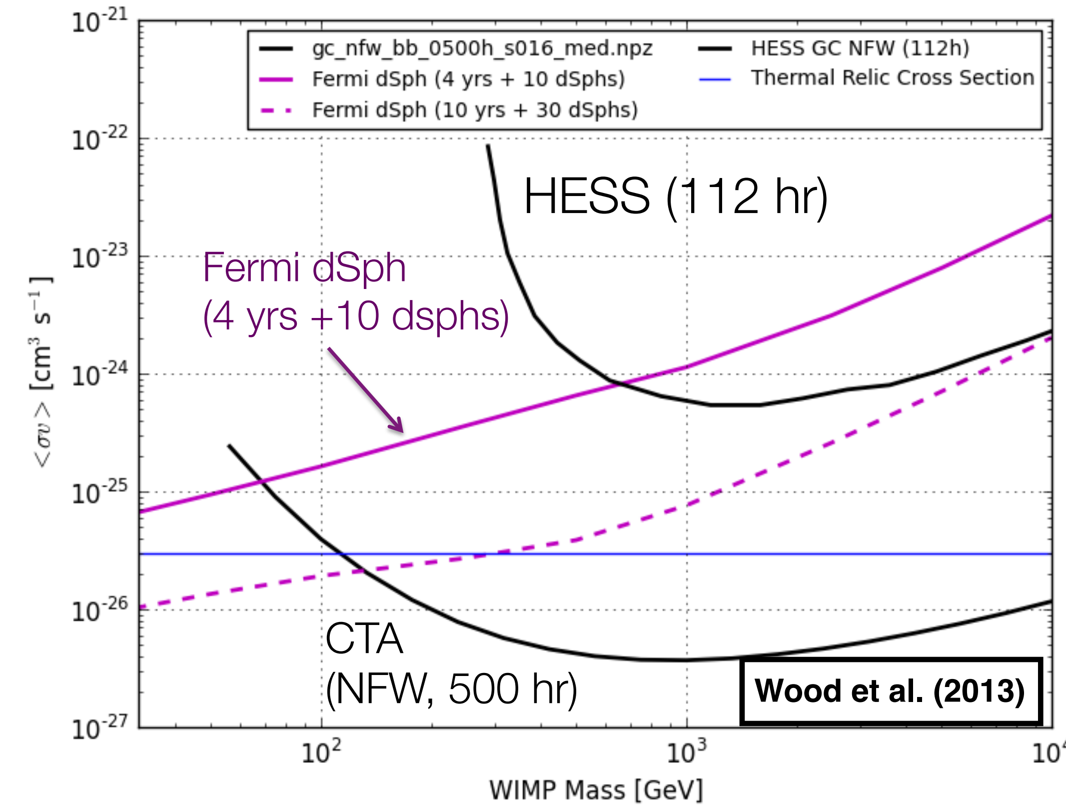
Residual Detector Pile-up

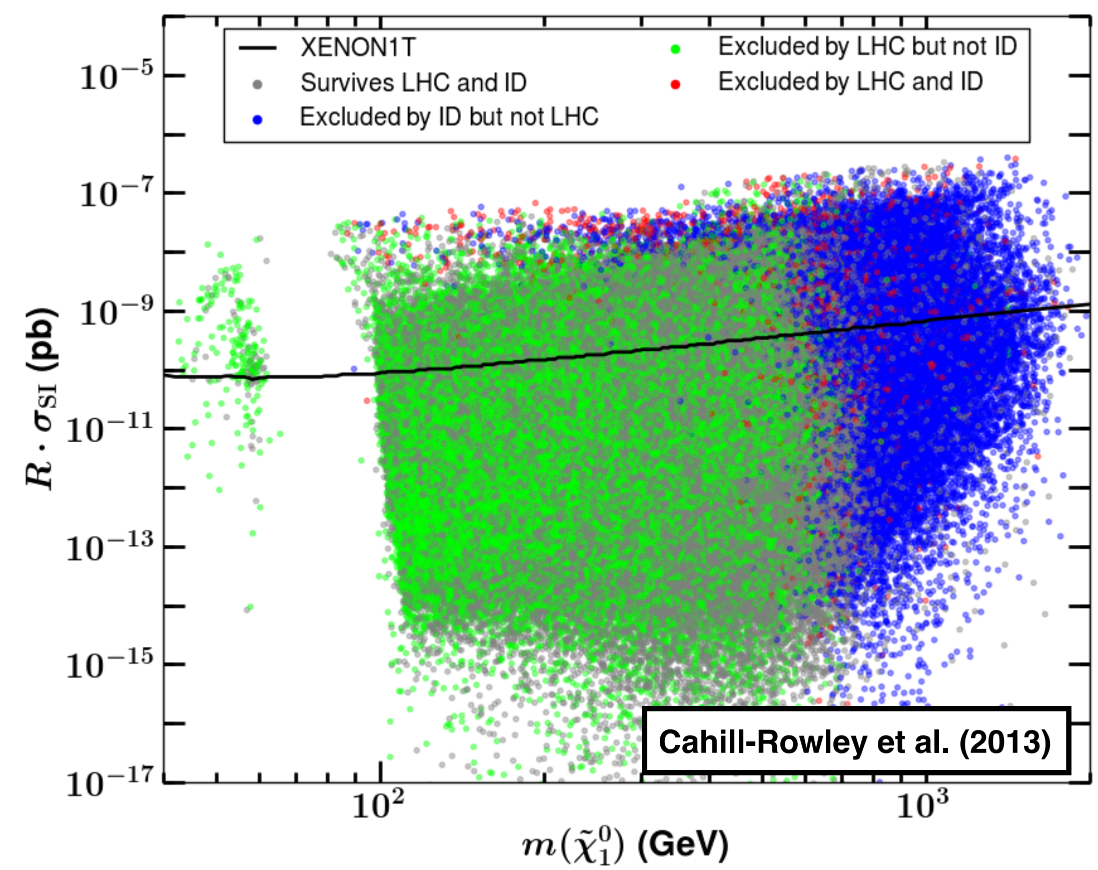


Cherenkov Telescope Array

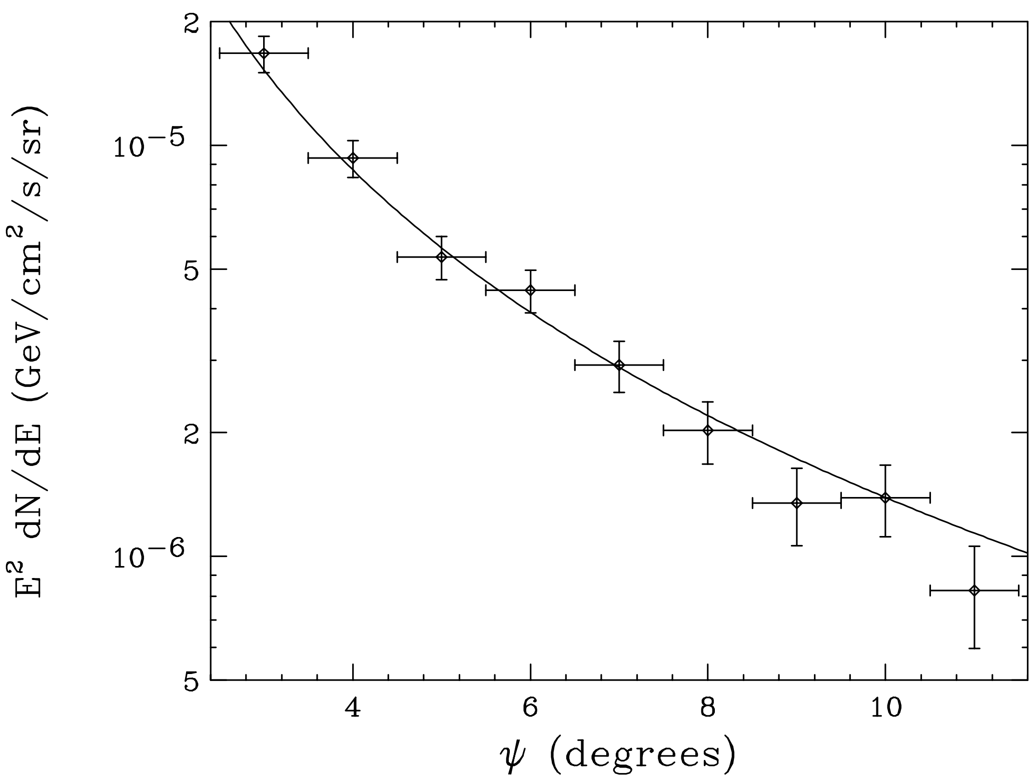


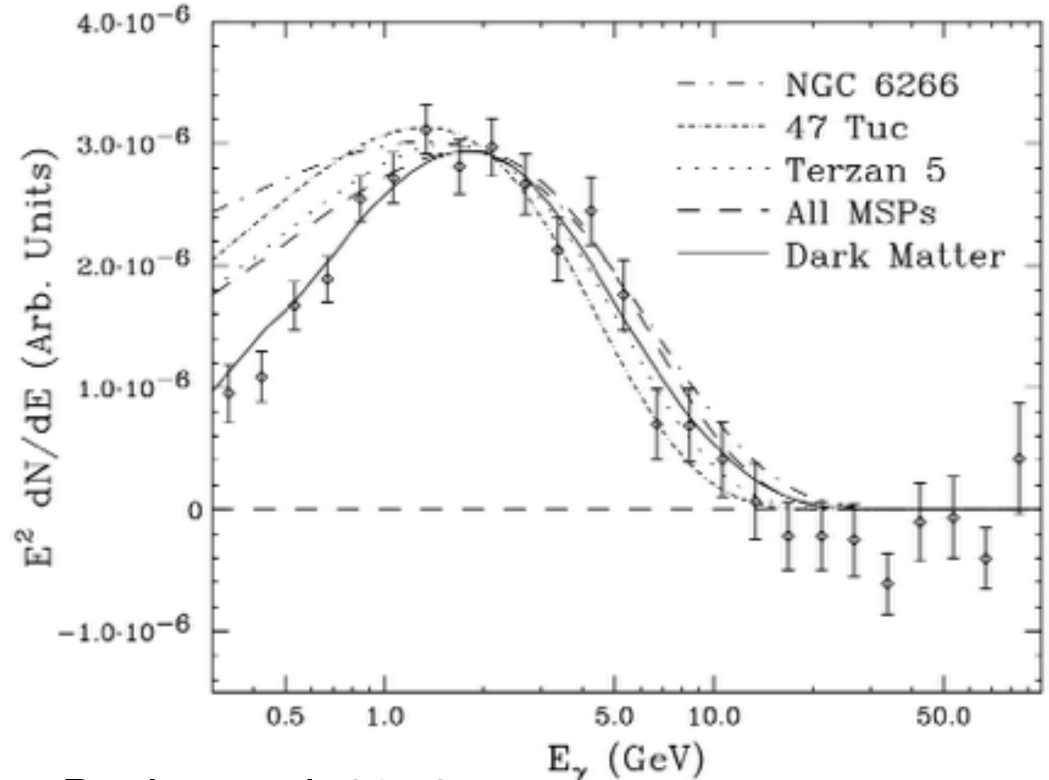
- **Ground-based array of air cherenkov telescopes**
  - **Better angular resolution**
  - **Larger effective area**
  - **Lower energy threshold**
- **Southern array**
  - **4 large (23m) telescopes**
  - **25 medium (9-12m) telescopes**
  - **Small (4m) telescopes covering >3km²**
- **US contribution could make order of magnitude improvement in the 100 GeV to 10 TeV range**





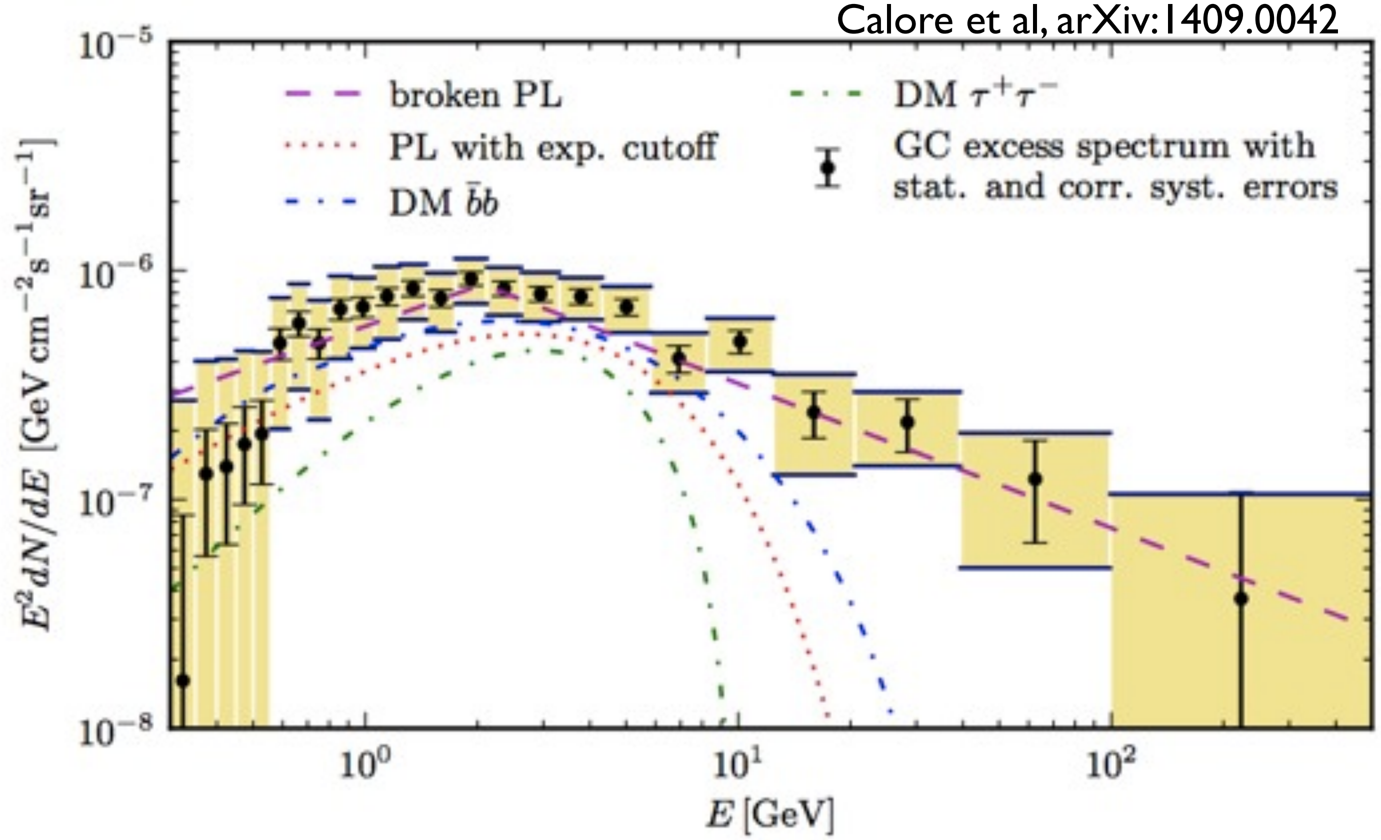
Back-up Slides:
Galactic Center





Daylan et al. 2014

Calore et al, arXiv:1409.0042



Low Energy Line Search
f_{sys} from Galactic Plane scans

- There are some common features likely from the effective area (Aeff)
- Displacement from 0 is mostly from Aeff, while spread is from bkg. modeling
- Larger systematic effect with wider windows (since power law approx. gets worse)